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VERSATILE DATA HANDLING SYSTEM STUDY

Final Report

NASA Contract NAS 5-21959

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SPACE AND COMMUNICATIONS GROUP

Hughes Ref. No. D0796 • SCG 40264R

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1. INTRODUCTION

The prime objective of the Versatile Data Handling System (VDHS) Study has been to arrive at recommendations for the most suitable image recording equipment for use with various spaceborne earth observation sensors. Future sensors presently under consideration were included in the study, as well as existing sensors and those under development. This study has been performed under contract to NASA/GSFC. Contract NAS 5-21959 defines six tasks as follows.

1.1 SENSOR REQUIREMENTS

The imagery requirements of the MSS and other earth sensors should be reviewed for possible commonality of data processing equipment.

1.2 SURVEY OF IMAGE RECORDING EQUIPMENT

An image recording equipment survey will be conducted and the characteristics of commercial imaging recorders, both in production and under development, will be reviewed for evaluation of the suitability of each recorder for use with the various sensors.

1.3 SENSOR/RECORDER COMPATIBILITY STUDY

From the data compiled in Task II*, a list will be prepared showing the imaging recorders which appear potentially suitable for use with one or more of the sensors. The equipment listed shall have a commonality of application with such equipment as Bench Test Equipment, Spacecraft Integration Test Equipment, and Operational Ground Terminal Equipment. Cost effectiveness and the possiblity of commonality are to be major considerations.

1.4 MODIFICATION STUDY

In cases where one of the recorders appears to meet most, but not all, of the requirements for a given application, the possibility of modifi-

*Subsection 1.2

cations will be explored. This will include both modification of the existing recorder design and the additional peripheral equipment to achieve compatibility.

1.5 MODULARIZATION STUDY

Since there are several variations of new sensors being considered, which results in a diversity of image recording requirements, the possibility of a modularized image recording system shall be studied. If practical, modularization would allow the use of a few standardized components with a minimum of specialized equipment to meet the various sensor requirements.

1.6 COMPLETE STUDY CONSIDERATION

At the conclusion of the above tasks, show by example and accompanying analysis how the concepts studied could result in developing a low cost data processing ground system for a given sensor such as the MSS or the Very High Resolution Radiometer.

2. SENSOR REQUIREMENTS

The sensors selected by the GSFC Technical Officer for inclusion in this study are:

Very High Resolution Radiometer (VHRR)

Advanced Very High Resolution Radiometer (AVHRR)

Multispectral Scanner System (MSS) (Local Station Only)

Improved MSS

Coastal Zone Color Scanner (CZCS)

Thermatic Mapper

High Resolution Pointable Imager (HRPI)

The characteristics of these sensors which impact on the design of their associated image recording equipment are summarized in Table 2-1.

2.1 SCANNING SPEEDS

A review of the sensor characteristics, as summarized in Table 2-1, shows that the speed requirements fall into two distinct categories. The VHRR, the AVHRR, and the CZCS all operate at line rates in the range of 360 to 480 lines per minute. On the other hand, the three variants of the MSS, the Thermatic Mapper, and the HRPI (all of which scan multiple lines per sweep), generate line rates an order of magnitude or more greater. In terms of present day image recorder technology, the 360 to 480 lines per minute speed range would be considered moderate, whereas the 4900 to 38,000 range would be considered very fast.

2.2 SYSTEM ECONOMICS

In the design of high quality image recorders, the requirement for high speed operation contributes very substantially to complexity and cost.

TABLE 2-1. SENSOR CHARACTERISTICS

Sensor	Status*	Scans/sec	Lines/scan	Lines/min	IGFOV**/ line	Duty Cycle, percent
VHRR	O	6.66	1	400	3200	30
AVHRR	D	6	1	360	3500	30
MSS	O	13.62	6	4,903.2	2346	45
CZCS	D	8	1	480	1618	22.3
Improved MSS***	P	27.24	6	9,806.4	1173	45
Improved MSS †	P	18.2	12	13,104	633	45
Thematic mapper ††	P	20	16	19,200	8800	40
HRPI, Hughes ††	P	37	18	39,960	4000	42.5

*O = Operational, D = Developmental, P = Planned.
**IGFOV = Instantaneous Geometric Field of View.
***Width of swath scanned = 25 n.mi.
†Width of swath scanned = 25 km
††Characteristics listed for the Thematic Mapper and HRPI are tentative only.

It, therefore, becomes apparent that those image recorders which are capable of satisfying the high speed requirement will not be economical for use with the low speed systems.

It is interesting to note here that, if the above systems are considered in terms of their intended functions, they again fall into two categories.

The VHRR and AVHRR are cloud imaging systems for meteorological use, so timeliness of the data is of the essence. There will, therefore, be a strong tendency for each user to want to receive imagery directly from the satellite, in real time. This will lead to a multiplicity of ground stations, and considerations of economy and simplicity will tend to dominate. Information available as to the CZCS system seems to show that this system will fall into this same category.

The remaining sensors from Table 2-1 will be used in various earth resource applications. Here, the data handling will tend to follow the pattern established by present ERTS system practices; that is, the data will be collected at a central facility where it will be processed. The processed data, including hard copy imagery, will then be distributed to the various users. For this reason only a few image recorders will be required, and the fact that they must be relatively expensive becomes tolerable.

2.3 COMMONALITY

One of the objectives of this study has been to examine the feasibility of using a single basic image recorder (perhaps with modifications) for all the designated sensor systems. The foregoing discussion makes clear that such feasibility does not exist. It will, however, be entirely feasible to specify two basic recorders, one for the lower speed systems and one for the high speed systems. This will be discussed in detail in Section 5.

3. IMAGE RECORDING TECHNOLOGY

Present day, high quality, image recorders fall into the following categories:

1) Cathode ray tube (CRT) recorders

2) Direct electron beam recorders (EBRs)

3) Mechanical scan recorders

   a) Crater lamp

   b) Laser

   c) Nonphotographic

4) Recorders using acousto-optical beam deflection (AOBD)

The salient characteristics of each type are summarized next.

3.1 CATHODE RAY TUBE RECORDERS

At the present time, most CRT recorders use the CRT deflection only to produce the line scan (usually horizontal), and the frame (or vertical) scan is provided by moving the photographic material in a direction orthogonal to the line scan at a line-by-line rate. These recorders are referred to as CRT line scanners. In the early recorders of this type and in some current designs, a lens system was used to image the scanned line from the CRT phosphor onto the photographic medium. More recently CRTs with fiber optic faceplates have been used. In this case the photographic material is placed in direct contact with the faceplate, and the fiber optics couple the image from the phosphor to the photographic surface without loss of resolution.

The advantages of fiber optic coupling are: much higher optical efficiency than a lens system, simplicity, and relative immunity to vibration. The principal disadvantage is "fiber optic signaturing" (also known as the "chicken wire effect"). This is due to slight nonuniformities in the fiber optic bundle, and manifests itself as faint parallel streaks orthogonal to the line scan. The density variation is slight, and if random, would be

unnoticeable; however, because it is coherent, the human eye readily picks it out. Fiber optic CRTs have improved greatly in this respect during the past several years. Continuing efforts toward improvement are being made, and it appears possible that within a few more years, fiber optic signaturing will cease to be a problem.

In addition to the CRT line scanners, CRT raster scan recorders have been built. In these, the photographic material remains stationary and CRT deflection provides both the line and frame scans. A lens system is used to image the raster so generated onto the photographic medium. There appears to be little activity or interest in raster scan recorders for high quality recording at this time.

3.1.1 CRT Advantages

1) Potential ruggedness. They have been used successfully under adverse environmental conditions for which the precise mechanisms of mechanical scan recorders would be poorly suited.

2) The line scan rate can be varied dynamically during the scan to compensate for geometric and/or timing errors in the incoming data.

3.1.2 CRT Limitations

In any attempt to use a CRT for truly high quality recording, certain problems arise. These include:

1) A practical resolution limit of the order of 4000 pixels (picture elements) per line

2) Difficulty in achieving precisely linear deflection

3) Difficulty in maintaining a precisely focused spot during intensity modulation and deflection

4) Nonuniformity of the phosphor, which degrades the signal-to-noise ratio.

Several years ago, an outstanding raster scan CRT recorder was developed using Polaroid film as the recording medium. A very well engineered system, it used some ingenious and effective techniques for minimizing the effects of phosphor nonuniformity and dynamic defocusing. It is probably safe to say that this instrument still represents the state of the CRT recording art, so far as image quality is concerned. Yet the images produced by it appear far inferior to those produced by some much simpler and less expensive mechanical scan recorders. The reason for this seems to lie in the nature of the CRT spot itself.

3.1.3 Cost of CRT Recorders

For low-to-medium quality image recording, CRT recorders can be built simply and economically; however, when the attempt is made to overcome the natural limitations of the CRT, listed above, through technical sophistication, both complexity and cost escalate rapidly and the resulting CRT recorders can no longer be considered cost effective.

3.2 DIRECT ELECTRON BEAM RECORDERS

Direct electron beam recorders (EBRs) are similar to CRT recorders in that modulation is applied electrically to the electron beam which is then magnetically (or electrostatically) deflected. In the EBR, however, the electron beam acts directly on the photographic material, as opposed to the CRT where the beam acts on a fluorescent screen whose light output is optically coupled to the photographic material. For this reason the photographic materi must be located inside the highly evacuated chamber where the electron be is generated. Thus, any practical EBR must include a sophisticated vacuum pumping system and equally sophisticated means for getting the photographic material into and out of the chamber.

Like CRT recorders, EBRs can be either line scanners or raster scanners. Because the electron beam is focused directly on the photographic material, extremely high spatial resolution is possible. This is partially offset by the fact that, because of problems associated with high vacuum operation, the largest film for which EBRs are commonly designed is 70 mm. Even so, resolutions of 10,000 pixels per line at 0.5 modulation transfer function (MTF) are being achieved, using ultrafine grain film.

3.2.1 EBR Advantages

1) EBRs are unique in their ability to record high quality imagery on a small format. When used with 70 mm roll film and automatic film processing, they are well suited for high volume production, and the 70 mm format is ideally suited to archiving.

2) Like the CRT recorders, the scan rate of an EBR can be dynamically varied to compensate for geometric and/or timing errors in the incoming data.

3.2.2 EBR Limitations

1) Because of the need to use fine grain roll film requiring wet processing, EBRs are poorly suited to single frame, quick look operation.

2) Because of the small image format, enlargement is necessary for visual interpretation.

3) The scan geometry is not inherently as precise as that with a high quality mechanical scan system.

4) Because of the requirement for high vacuum, EBRs are complex and costly and require skilled maintenance. Where high speed is not a requirement, a mechanical drum scanner can produce imagery of equal or better quality at a fraction of the cost.

3.3 MECHANICAL SCAN RECORDERS

At the present time, the highest quality line-by-line image recording has been done through the use of mechanical scan recorders. Resolutions greater than 20,000 pixels per line, as well as recording rates as high as 120,000 lines per minute, have been achieved. Mechanical scan is well suited to large image formats, line widths of 8 to 22 inches being typical. For direct visual interpretation, this is an advantage, but for archiving great quantities of imagery, it is a disadvantage.

The cost of mechanical scan image recorders varies over a very wide range, depending largely on the speed and resolution requirements, and whether the instrument is in production or is one of a kind. Actually, high speed appears to be more costly than high resolution, there being available instruments in the $10,000 price class which will produce excellent imagery with resolution of better than 4000 pixels per line if the speed is limited to a few hundred lines per minute.

There are two basic types of mechanical scan image recorders: drum scanners and flatbed scanners.

3.3.1 Drum Scan

In drum scanning, the material on which the image is to be reproduced is wrapped around a revolving drum. Rotation of the drum produces the line scan — one line per revolution. Frame scan is accomplished through axial motion of an optical carriage (or stylus in nonphotographic systems). The carriage is driven by a precision lead screw which advances it one line width for each revolution of the drum.

The almost complete absence of geometrical distortion achievable by this type of scan is of great value in applications where the output images are to be used in photogrammetry, and the very uniform line-to-line spacing contributes to the excellent cosmetic quality of the imagery produced by these recorders. On the other hand, the fact that the line scan is produced by a high inertia system makes drum scan poorly suited to applications where the scan rate must be varied to compensate for geometrical distortions in the incoming data.

Drum scanning is well suited to speeds up to about 3600 lines per minute and is very economical, particularly at the slower speeds.

A disadvantage to drum scanning, which may be serious in some applications, is that the film or paper has to be loaded onto the drum for each recorded image. Several excellent instruments exist which load paper or film onto the drum automatically, and remove and process it automatically at the end of the recording; however, they are necessarily complex.

3.3.2 Flatbed Scan

The second basic type of mechanical scan image recorder is the flatbed line scanner. Here the line scan is commonly provided by either a mirror galvanometer, a rotating prism, or in the case of nonphotographic recording, by a moving stylus. The orthogonal, or frame, scan is provided by moving the paper or film on which the image is being recorded, as in the case of the CRT and EBR line scanners discussed previously.

Flatbed mechanical scan may be chosen for use in certain applications because is has three principal areas of superiority over drum scan. These are:

1) No drum loading and unloading are required.

2) Recordings may be made in a continuous strip, rather than by discrete frames.

3) Higher speeds are possible.

There is one problem in common with CRT and EBR line scanners from which flatbed scanners suffer. This is the difficulty of moving the recording material with sufficient uniformity to prevent the grouping of scan lines. On the surface, this may seem like a trivial problem, or at least one which could be solved by a little competent engineering; however, through the years, one line scanner design after another has run aground at this very point. Experience shows clearly that this is indeed a knotty problem which demands careful attention.

3.3.3 Flatbed Line Scan

As mentioned previously, there are three common types of flatbed line scans:

1) Mirror galvanometer

2) Rotating prism

3) Electrical stylus

Of these, the rotating prism, used to deflect a modulated laser beam, is by far the fastest and most expensive. The reason for the high cost lies in the difficulty of fabricating and controlling the prism with sufficient precision to avoid line grouping. This can be done, however, with excellent results and with speeds to 120,000 lines per minute achievable.

Both the mirror galvanometer and the moving stylus techniques are relatively simple and inexpensive. The galvanometer, like the rotating prism, is used to deflect a modulated laser beam, but is inherently much slower. The electrical stylus may record in any of several ways: thermally, electrolytically, or electrostatically. At the present state of the art, the electrostatic method produces by far the best images of the three, which can be comparable in quality to those produced photographically. The principal limitation of stylus recording is its low speed, which at the present time is limited to about 200 lines per minute for high quality recording.

3.3.4 Line Scan Linearity

The linearity of all the mechanical line scan systems discussed here is inherently good, and entirely adequate for most applications without further refinement; however in multispectral recording where there is a requirement for image registration to within a fraction of a pixel, certain second order effects become significant. The hunting of a synchronous motor used to drive a drum or rotating prism can, for example, cause small but possibly significant nonlinearities. Galvanometer scan is not as inherently precise as either drum or rotating prism scan, particularly when an attempt is made to operate the galvanometer at high line rates and/or with excessively short retrace time. Under these conditions, the mechanical resonance of the galvanometer becomes significant and the scan tends to become sinusoidal.

In systems where the input data is stored digitally in a buffer, there is a practical technique for eliminating all these residual nonlinearities. This is done by making the image recorder generate the word clock which is used for reading out the buffer, this generation being done on the basis of equal scan angle increments rather than equal time intervals. For example, on a drum scanner, an optical tachometer disk having the proper resolution can be mounted on the drum shaft and used to generate one clock pulse per pixel. On a rotating prism or mirror galvanometer scanner, the same mirror that generates the image can simultaneously scan a high resolution optical grating and, again, generate one clock pulse per pixel. In extremely high resolution systems where providing an optical track of sufficiently high resolution becomes impractical, the clock can be generated by an oscillator which is phase locked to a multiple of the optically generated frequency.

3.3.5 Light Sources for Mechanical Scan Recording

Any mechanical scan image recorder producing a photographic image requires a modulated light source. The three commonly used ones are:

1) Crater lamps

2) Internally modulated lasers

3) Externally modulated lasers

Crater Lamps

The earliest truly high quality photofacsimile recorders used zirconium crater lamps (also known as "glow lamps" and "glow modulator tubes") as a modulated light source. This technique is still in common use, and recorders using it are capable of producing photofacsimile copies which rival the transmitted original in every respect. Resolutions as high as 1000 lines per inch and gray scale fidelity limited only by the photographic materials available have been achieved using the crater lamp.

In contrast to CRT and EBR image recorders which commonly employ a round, statistically defined scanning spot, crater lamp recorders generally use a sharply defined rectangular spot. This situation allows the height (assuming horizontal scan) of the spot to be adjusted to yield exactly contiguous scan lines, thus effectively minimizing the visibility of the line structure. At the same time, the width of the spot can be made substantially smaller than its height, to the point that the spot width causes no degradation of the overall resolution capability of the system. It is common for recorders of this type to exhibit substantially greater transverse resolution than line-to-line resolution, which is limited by the chosen number of scan lines per inch. This accounts, in part, for the astonishing sharpness of the images produced by such recorders.

Crater lamps are very economical (about $15.00). Their principal limitations are limited light output and limited bandwidth (approximately 1 MHz). The limited light output dictates the maximum recording speed which can be used with a given photographic material and completely precludes the use of some of the very slow materials, such as dry silver (see subsection 3.7.2).

Internally Modulated Lasers

Certain helium-neon (He-Ne) lasers can be internally modulated, and they are sometimes operated in this mode; however, both the bandwidth and dynamic range can be improved by using external modulation (discussed next). The predominantly red output of the He-Ne laser requires that any photographic material used with it be red sensitive. This severely limits the choice of recording material. It also introduces an element of inconvenience (which may in some cases be serious), since it means that the material cannot be handled under the orange or red darkroom safelights which are used with the common blue sensitive materials.

Externally Modulated Lasers

For high speed recording where the light output of the small He-Ne lasers is insufficient, or in cases where the predominantly red output cannot be used, helium-cadmium (He-Cd) lasers are commonly used. They have a high output in the blue-green spectral region and are well suited for use with a wide range of photographic materials. In general, He-Cd lasers tend to have a "noisy" output, that is, subject to small random fluctuations. This is

recognized, and there are proprietary schemes for circumventing this problem. Since He-Cd lasers are not suitable for internal modulation, they are always used with external modulators.

Laser Modulators

Until very recently, the laser beam modulators in common use were electro-optical devices, such as the Kerr cell and the Pockel's cell. In image recorder design, these have now been largely replaced by acousto-optical devices which are simpler and capable of handling much greater bandwidths. The acousto-optical modulator (AOM) consists essentially of a transversely excited glass (or other transparent) plate, in conjunction with a schlieren optical system. They are commercially available, and are being incorporated into an increasing number of image recorder designs.

3.4 RECORDERS USING ACOUSTO-OPTICAL BEAM DEFLECTION

The use of acousto-optical beam deflection to provide line scan in image recording is relatively new. So far as we have been able to determine, there are no image recorders presently in production which employ this technique, however, some successful developmental work along this line has been done, particularly by Radiation, Inc.

The acousto-optical beam deflector (AOBD) is used to angularly deflect a laser beam. It is essentially an electrically driven diffraction grating combined with a suitable optical system. The diffraction grating is formed by generating an ultrasonic transverse wave in a suitable transparent medium. The carrier frequency can be of the order of 100 MHz.

Like mirror galvanometers, previously discussed, AOBDs are best suited to use in flatbed recorders where frame scan is accomplished mechanically. The advantage of AOBDs over galvanometers is that the achievable scan speeds are much higher for the former. At rates much above 50 lines per second, the use of galvanometers for linear scan becomes questionable depending upon other factors such as the duty factor and linearity required. With AOBDs very high scan speeds can be achieved; however, the resolution presently obtainable in such sytems is only about 1000 to 1500 pixels per line.

Either internally or externally modulated lasers, discussed in subsection 3.3.5, can be used as a modulated light source in the design of AOBD image recorders.

3.5 DYNAMIC RANGE

In image recording, the term "dynamic range" is used to refer to the length of the gray scale, that is, the difference in density between whitest white and blackest black. The density corresponding to whitest white is commonly referred to as D_{min}, and that corresponding to blackest black as D_{max}.

In a well designed photographic image recorder, the dynamic range is commonly limited only by the recording medium used, which is another way of saying that there is enough light available to expose the film or paper to whatever D_{max} the medium is capable of. In general, the dynamic range of films is much greater than that of paper. Hence, despite the inconvenience, photographic transparencies are used in preference to paper prints in most critical applications.

Density is defined as the logarithm of the relative amount of light transmitted. Hence, a density of 1.0 means that 1/10 of the incident light is transmitted, and a density of 2.0 means that 1/100 is transmitted. In the case of opaque images such as paper prints, the same rules apply except that the amount of light reflected is considered, rather than that transmitted.

The dynamic range of photographic papers is commonly in the range of 1.5 to perhaps a little over 2.0. That of film may be more than 3.0.

In discussions of dynamic range, one sometimes hears talk of "how many shades of gray" a certain system will reproduce. At this point, it is vital to be sure what kind of shades of gray are being talked about. One criterion commonly used is called "square root of two gray shades," which means that the light transmitted at any given gray level is $\sqrt{2}$ times the light transmitted at the next darker level. Since the common log of $\sqrt{2}$ is 0.1505, this is the same as saying that each density level differs from the adjacent one by 0.1505. Hence, to reproduce 16 square root of two gray levels requires a $D_{max} - D_{min}$, or dynamic range, of 16 x 0.1505, or 2.4. The confusion in terminology arises from the fact that discussions sometimes center on "discernable shades of gray." This is a highly subjective matter, and certainly not quantitative. The number of discernable shades is usually quite high, compared to the number of $\sqrt{2}$ shades.

3.6 GRAY SCALE LINEARITY

The sensitivity of a photographic material is commonly represented by plotting image density against the common log of the corresponding exposure (usually stated in meter-candle-seconds). The resulting curve is called a "D-Log E" curve, or sometimes an "H and D" curve, after its originators, Hurter and Driffield. Such a curve for a typical photographic film is shown in Figure 3-1.

D-Log E curves are generally more or less S shaped, as shown, the degree of curvature being a function not only of the photographic material, but of the developer chemistry and developing technique. In conventional photography, this results in compression of both the highlight and the shadow ranges, and the photographer must choose not only the proper exposure but the proper film and its development to achieve the gray scale rendition he desires.

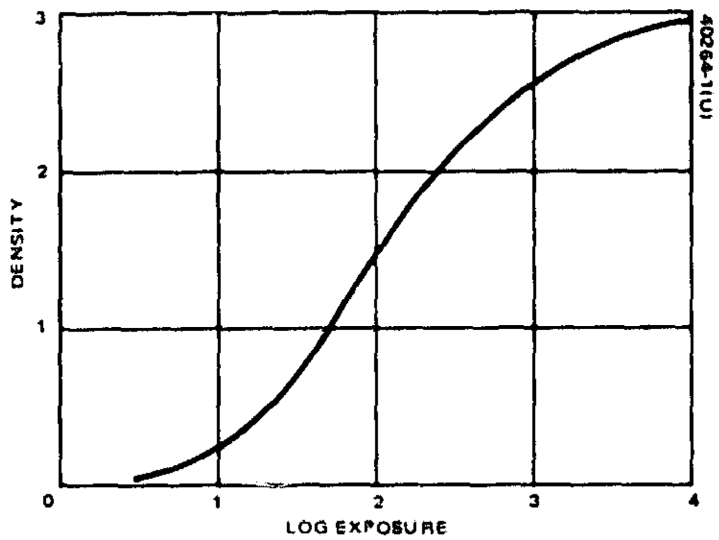

FIGURE 3-1. D-LOG E CURVE FOR TYPICAL FILM

Image recording provides the opportunity of correcting electrically for the nonlinearity of our chosen photographic material. This is sometimes referred to as gamma correction, from the fact that the slope of the D-LOG E curve is traditionally called gamma (γ). Since such techniques are used not only to correct the γ of the photographic material but to correct for other system nonlinearities, and sometimes to introduce other nonlinearities for special reasons, a better term is probably linearity compensation.

Linearity compensation can be accomplished through the use of a nonlinear amplifier at the input to the image recorder. The nonlinear characteristic must be adjustable, and this is usually done by approximating the desired curve by a number (usually three to five) of straight line segments, each with adjustable gain and threshold. The design of such amplifiers has been the subject of much attention, but at best they have a number of controls, more or less interacting, and their proper adjustment can be a time-consuming nuisance.

In systems where the input to the image recorder is processed digitally, a more attractive and flexible method for linearity correction is through the use of a digital memory or "look-up table." In this technique, every possible incoming word, each representing a certain signal level, locates a particular address in the memory, and stored at that address is a new word representing the desired output level. Thus, any conceivable correction curve can be realized.

3.7 RECORDING MATERIALS

Where the highest quality imagery is required, conventional wet process photographic film is used, since its resolution, dynamic range, and geometric stability are superior to those of any other medium.

3.7.1 Stabilization Paper

Where economy, fully automatic operation, and quick look capability are important, and the dynamic range of film is not required, stabilization paper gives the best results. It is fast enough for use with crater lamp recorders, and images recorded on it are comparable with those made on the best conventional photographic papers. At least one type has a density range of 2.1 and can reproduce 14 $\sqrt{2}$ gray shades, which is excellent for paper.

Stabilization paper is unique in that the developer chemistry is contained in the paper stock itself. After exposure, the paper is run through an automatic two-bath processor, which yields a ready-to-use print in about half a minute. The print, as delivered, is very slightly moist, and dries quickly. It is of excellent quality, there is no visible mottling, and the color is good black and white. The print, as delivered from the processor, is semipermanent, which means that it may be kept for several months without visible deterioration, and subsequent deterioration is gradual. If archival permanence is desired, the print may, after its initial use, be fixed in a hypo bath and washed, making it as permanent as any conventional photographic print.

3.7.2 Dry Silver Materials

Despite the excellent performance of stabilization paper, the fact that its processors use wet chemicals which have to be changed at intervals is something of a nuisance, and through the years, substantial efforts have been devoted to the development of dry process materials. At this time, the most promising of these appear to be the dry silver films and papers, and a number of image recorders have been developed to use them.

Dry silver materials have been developed by, and are available from, the 3M Company, whose current data book lists two types of paper and four types of film. All of these materials are developed thermally, after exposure, by heating to a temperature in the vicinity of 260° F.

Of the dry silver papers listed in the 3M catalog, the best one for continuous tone (gray scale) recording is type 7742. Its spectral sensitivity is greatest in the blue-green. It is some two orders of magnitude slower than stabilization paper, and has a density range of only about 1.5. It has a limited shelf life (6 months under average conditions), and after exposure the image deteriorates gradually at a rate which depends upon storage temperature and humidity.

The sensitivity of type 7742 paper is so low in the spectral range of He-Ne laser output that the designers of He-Ne recorders formerly chose to use type 7770. This paper was originally intended for binary black and white recording rather than continuous tone work, and images recorded on it frequently had a rather mottled appearance. More recently, the 3M Company has developed a type 7771 paper specifically for continuous tone recording with He-Ne lasers. It is so new that it is not listed in the current 3M data book, but users report that it is quite satisfactory and continuing to improve.

There are two dry silver films commonly used for continuous tone image recording. Type 7859 is blue-green sensitive, and therefore suited for use with He-Cd lasers. It has a density range of about 2.2. Type 7869 is red sensitive (panchromatic), and so is well suited to He-Ne laser recording. Its density range is about 3.1, considerably better than that of type 7859; also, its D-Log E characteristic is considerably more linear. Being panchromatic, darkroom handling is more of a problem than with type 7859.

3.7.3 Dry Silver Processing

For good image quality it is vital that during thermal development the temperature be uniform over the surface of the print, and to this end various processors have been developed. Dry silver paper can successfully be run between heated rollers. With the present films, this technique will not work because the heat softens the gelatin emulsion to the point where it would either stick to the roller or be deformed by it. Therefore, contact can be made to only one side of the film during processing, which leads to problems.

At present, there are successful film developers which operate on a continuous feed basis, such as where the film feeds off a roll, through the recorder, and thence through the processor. There are, however, to this writer's knowledge, no successful single sheet film processors such as the ones available for dry silver paper. For quick look operation, this situation is fairly serious, since the only way to get a picture out of the processor is either to record the next one or to waste one picture's worth of film. It is understood that 3M has under development hard surface films which are intended to be processed like dry silver paper, but no commitments have been made as to when these may become available.

3.7.4 Nonphotographic Materials

Nonphotographic electric stylus recording has been around for many years. Such systems have the advantages of low cost and convenience, however, until very recently, none of the recorded imagery was comparable in quality to that produced by photographic recording. The technique which makes high quality, nonphotographic reproduction possible is dielectric paper recording. The stylus scans out a charge pattern on dielectric paper, which is subsequently toned with finely dispersed carbon, much as in a Dennison or SCM office document copier. One of the very attractive aspects of this system is the very low cost of the paper - approximately 1.8 cents for an 8 x 10 inch picture, at present prices.

4. SURVEY OF AVAILABLE IMAGE RECORDERS

As the result of previous work in this field, a rather complete listing of manufacturers of image recording equipment was at hand at the start of the present study. This listing is reproduced as Appendix A of this report, for reference. Table 4-1 is a listing of the manufacturers contacted for this study, together with brief comments on the results of the contacts.

Table 4-2 contains a summary of all the image recorders surveyed which, it is felt, should be of interest to this study. It will be noted that the only ones which can be considered proven products are crater lamp recorders. These are all excellent designs and have proven themselves through the years, but all are limited by the modest light output of the crater lamp and may be considered obsolescent. They are listed here, however, because of the fact that they give excellent performance and can be outstandingly cost effective, particularly for use in bench test and integration test equipment. It should be noted that some of these older recorders have been converted experimentally to laser operation and these developmental efforts are continuing.

In contrast to crater lamp recording, which is a well established art, laser recording technology is still in its infancy. Great strides have been made in the last few years, and this rate of progress appears to be continuing. For this reason it may be unwise to attempt at this time to select an image recorder for use with a proposed scanner which is several years downstream.

For completeness, several image recorders have been included in Table 4-2 even though they do not meet the requirements as to speed and/or resolution of any of the sensors listed in Table 2-1. For example, the D-700 and K-300 are too slow, and the MRCR-2 has marginal resolution. The DRGS and the HRD are too slow for use with the high speed sensors, and much too expensive for use with the low speed sensors only.

The following paragraphs contain more detailed descriptions of those image recorders which will be given particular attention in the report of the Compatibility Study (Section 5).

4.1 LR-72 CHARACTERISTICS

Of the image recorders included in in this survey, the LR-72 manfactured by RCA is capable of the highest performance on all counts. Its maximum speed of 120,000 lines per minute and its resolution capability of 20,000 pixels per line make it

TABLE 4.1 VENDORS CONTACTED DURING THIS STUDY

Manufacturer	Comments
3M, Mincom Division	Manufactures EBR recorders
3M, Microfilm Products	Manufactures dry silver photographic materials
CBS Laboratories	Primarily a research and development facility, not geared to volume production
EDO Western Corp	Manufactures CRT fiber optic line scan recorders. Not suitable for VDHS applications
EG&G, Inc	Manufactures an interesting nonphotographic recorder
EMR Aerospace Sciences	Formerly manufactured CRT line scan recorders. Has recently abandoned this activity.
General Scanning, Inc	Principal supplier of scanning galvanometers
Image Information, Inc	Interesting developmental work in laser recording. Just recently bought up by Muirhead, Inc
Litton Industries, Datalog Division	Sells several image recorders of possible interest.
Muirhead, Inc	Company has a long established record for excellent photofac simile recorders. Recent work in laser recording
Perkin Elmer Corp	Until this year, active in developing advanced image recording techniques. Has now abandoned this line of work.
Radiation, Inc	In production of the Laserphoto image recorder for Associated Press. Also work in advanced recording techniques.
RCA	Active in the development of advanced laser recording tech niques. Two recorders of interest to this study.
Westinghouse	Manufacturing and support capability for the DRGS image recorder, with continuing redesign and marketing effort.
Zenith Radio Corp. Optical Systems Group	Manufacturer of acousto optical modulators, acousto optical beam deflectors, and lens systems.

more than adequate for use with any of the scanners included in this study. Its price of $120,000, however, means that it would be far from cost effective for use with the low speed scanners. The LR-72 is a flatbed recorder using a rotating prism, or multifaceted mirror, for line scan, and a proprietary continuous film drive for frame scan. The frame scan appears to be particularly good, and this is said to be one of the few very high resolution recorders capable of producing imagery which is free from visible line grouping. The light source is a He-Cd laser, with AOM. A proprietary technique is used to nullify the effects of the characteristic He-Cd laser noise. This recorder is normally used with conventional wet process film in order to realize the full image quality of which the recorder is capable. However, dry silver film could be substituted if the resulting degradation in image quality can be

TABLE 4.2. IMAGE RECORDER CHARACTERISTICS

Manufacturer	Model	Material	Recording Method	Image Width, in	Scan	Lines Per Minute, Maximum	Pixels Per Line	Developmental Status	Budgetary Cost, dollars
Litton Datalog	Pressfax 501	Conventional film	Crater lamp[1]	15.4	Drum, manual load	2,000	10,000	Proven product	40,000
Litton Datalog	MRCR 2	Stabilization paper[2]	Crater lamp	7.8	Drum, auto load	360[3]	1,800	Proven product	15,000
Muirhead/Image Information, Inc	Pagefax K-661	Conventional film	Crater lamp[6]	24	Drum, manual load	3,600	24,000	Proven product	35,000
Muirhead/Image Information, Inc	D 700	Conventional film or paper	Crater lamp	10	Drum, manual load	240	6,000	Proven product	10,000
Muirhead/Image Information, Inc	K 300/K 560[17]	Stabilization paper[2]	Crater lamp[5]	10 or 8	Drum, auto load	240[18]	4,000	Proven product	15,000
Muirhead/Image Information, Inc	High Resolution Display (HRD)	Dry silver film[2]	He-Cd laser with AOM	9	Drum, auto load	1,000	13,850	Developmental	150,000
Muirhead/Image Information, Inc.	VHRR-F-K	Dry silver film[2]	Argon-ion laser with AOM	8.55	Galvanometer	400	3,800	Developmental[13]	57,000
Radiation, Inc.	Laserphoto	Dry silver paper[2]	He-Ne laser with AOM	8	Galvanometer	160	1,280	New product[8]	4,000
Radiation, Inc.	Laserphoto, police model	Dry silver paper[2]	He-Ne laser with AOM	8	Galvanometer	2,400	2,200[16]	Developmental	12,000
RCA	LR 73	Dry silver film[2]	He-Ne laser with AOM[9]	9	Galvanometer	24,000	2,200[10]	Developmental	10,000[11]
RCA	LR 72	Conventional film	He-Cd laser with AOM	8	Rotating prism	120,000	20,000	New product[12]	120,000
Westinghouse	DRGS	Dry silver film or paper	Argon-ion laser[14] electro optical modulator	21	Drum, auto load	1,100	14,000	Developmental[15]	
EG&G	News Picture Receiver (NPR)	Dielectric paper[2]	Stylus	9.5	Flatbed	120	1,900	New product[7]	8,000[4]

1) One unit has been modified to use a He-Cd laser. It has been delivered, and is in regular use.
2) Includes automatic processing.
3) One unit has been modified to operate at 480 lines per minute. It has been delivered and is in regular use.
4) Price includes digital electronics.
5) One unit has been modified to use a He-Ne laser, internally modulated, and dry silver paper.
6) One unit is currently being modified to use a He-Cd laser and AOM.
7) Four prototype units have been built from production drawings, full production scheduled for summer 1974.
8) Two production units have been delivered with 60 more to be delivered in July 1974, and 60 per month henceforth to a total of 1500.
9) He-Cd laser with AOM available as option.
10) With the addition of field flattening optics, at a cost of several thousand dollars, this can be increased to 4000 pixels per line.
11) Target price for a reasonable production quantity, including digital electronics.
12) Several delivered and in use.
13) One developmental unit delivered and in use.
14) Second unit modified to use He-Ne laser with electro-optical modulator.
15) Two units delivered and in use.
16) Resolution can be increased to at least 4000 pixels per line, in the opinion of the manufacturer.
17) The K 560 is a modification of the proven K-300, new drum motor, new processor, repackaged electronics. Can be fitted with He-Ne laser.
18) One K 300 has been delivered operating at 360 rpm. 400 rpm is probably feasible, but not much more.

tolerated. The film used is 9.5 inches wide and the active width of the scan line is 8 inches. Several of these recorders have been delivered and are in use by a Government agency.

4.2 LR-73 CHARACTERISTICS

The LR-73, manufactured by RCA, is a galvanometer scan flatbed recorder designed for use with dry silver film. It uses a proprietary film drive for frame scan, and, like the LR-72, its output is said to be extraordinarily free from visible line grouping. Its normal resolution is quoted at 2200 pixels per line, but with the addition of field-flattening optics (at an additional cost of several thousand dollars), this can be increased to at least 4000 pixels per line. The film used is 9.5 inches wide, and the active length of the scan line is 8 inches. The maximum line rate is quoted as 24,000 lines per minute, which is extraordinarily high for a galvanometer recorder, and much too high for any known galvanometer to operate in a linear-scan mode. Since the quoted price includes a two line digital buffer, one can conjecture that, at this high speed, the galvanometer operates in a resonant mode producing essentially a sine wave scan, and that to compensate for this, the data is read out of the buffer nonlinearly. Since two lines of buffering are provided, this probably means that the back scan of the sine wave is also used. The possibility of using an optical track to generate a readout clock to ensure registration of imagery along the line in multispectral recording was discussed with RCA, and appears feasible. This recorder uses an AOM, with either a He-Ne or a He-Cd laser. There is an open question at this time whether or not the frame scan is repeatable enough to ensure registration within a fraction of a pixel in consecutive recordings; however, RCA intends to investigate this matter in the very near future and states further that representatives of GSFC will be invited to witness the tests. Because of the proprietary nature of much of the technology used in this recorder, information about it has been somewhat sketchy; still, enough has been learned to make it appear an excellent candidate for recommendation by this study. The LR-73 exists at present only as an engineering model, but RCA's stated intention is to develop it for the mass market with a target price of $10,000 including electronics.

4.3 LASERPHOTO CHARACTERISTICS

Laserphoto recorders are being mass produced by Radiation, Inc. under a contract from Associated Press International for 1500 units. The original engineering model of the Laserphoto was conceived and built at MIT. Subsequently, several so-called prototype models were built by Perkin-Elmer Corp. The production contract was then awarded to Radiation, Inc., where considerable reengineering was done before the design was put into production.

The Laserphoto is a galvanometer scan flatbed recorder, using a He-Ne laser with AOM, and recording on 11 inch dry silver paper with an active line width of 10-1/2 inches. It records at 160 lines per minute and 1280 pixels per line, these limits being established by the Associated Press

transmission circuits rather than by any limitations inherent in the recorder technology. Radiation, Inc. has recently proposed an advanced version of this recorder for police work which would record at 2400 lines per minute and 2200 pixels per line. The possibility of increasing the resolution to 4000 pixels per line has been discussed, and there seems to be no reason why this cannot be accomplished. If this can be done economically, the resulting image recorder might be very attractive for VHRR and AVHRR applications. The possibility of using dry silver film in place of dry silver paper has also been discussed. When and if the new hard surface films (subsection 3.7.3) become available, this substitution will present no problems, but with present films, it would require a complete redesign of the processor.

4.4 NPR CHARACTERISTICS

The news picture receiver (NPR) has been developed and put into production by EG&G, Inc., under contract to United Press International. It is unique among image recorders in that it achieves photographic quality reproduction with nonphotographic techniques. The paper used has a dielectric coating, but is not photosensitive. Recording is done by a single electrostatic stylus which scans out a charge pattern on the paper. The paper is then toned in an automatic processor, which creates a permanent image. The stylus is carried on a continuous belt which provides the line scan. As in other flatbed recorders, frame scan is provided by means of the paper drive.

It is characteristic of the toned dielectric paper technique that attempting to control gray level by varying the voltage applied to the stylus is not very successful. EG&G gets around this by a rather interesting approach. Since the inherent resolution of the medium is very high, each scan line is broken up into a finite number of elements, and by pulse-duration modulation, the area of each of these elements is controlled. (The details of this technique are proprietary.) The resultant image is, in effect, an exceedingly fine grain halftone.

Due to the use of the belt driven stylus scanning technique, the NPR records at a duty cycle of slightly less than 50 percent. Since this is incompatible with existing United Press transmission standards, the basic NPR includes a digital line buffer to compress the duty cycle of the incoming signal. Digital compensation of gray scale linearity is also included (see 3.6).

The NPR records at 120 lines per minute, with a resolution of about 1900 pixels per line — these parameters being based on the limitations of the United Press transmission circuits. The resolution limit is set by the smallest practical dot size in relationship to the length of the scan line. By doubling the width of the recorded image to 19 inches, the number of pixels per line could be doubled to something approaching 4000, but this would involve major redesign. The line rate can probably be increased to 200 lines per minute with no drastic changes to the existing design.

The test copy produced by the NPR is most impressive: both copies of ordinary photographs and IEEE test charts. The gray scale is excellent,

and the pictures have a sharpness and sparkle most unusual for a nonphotographic system. Figures 4-1 and 4-2 are reproductions of typical NPR sample copies. (The originals have been delivered to the VDHS Technical Officer.)

40264-2(U)

FIGURE 4-1. PORTION OF IEEE FACSIMILE TEST CHART, AS REPRODUCED BY NPR IMAGE RECORDER

40264-3(U)

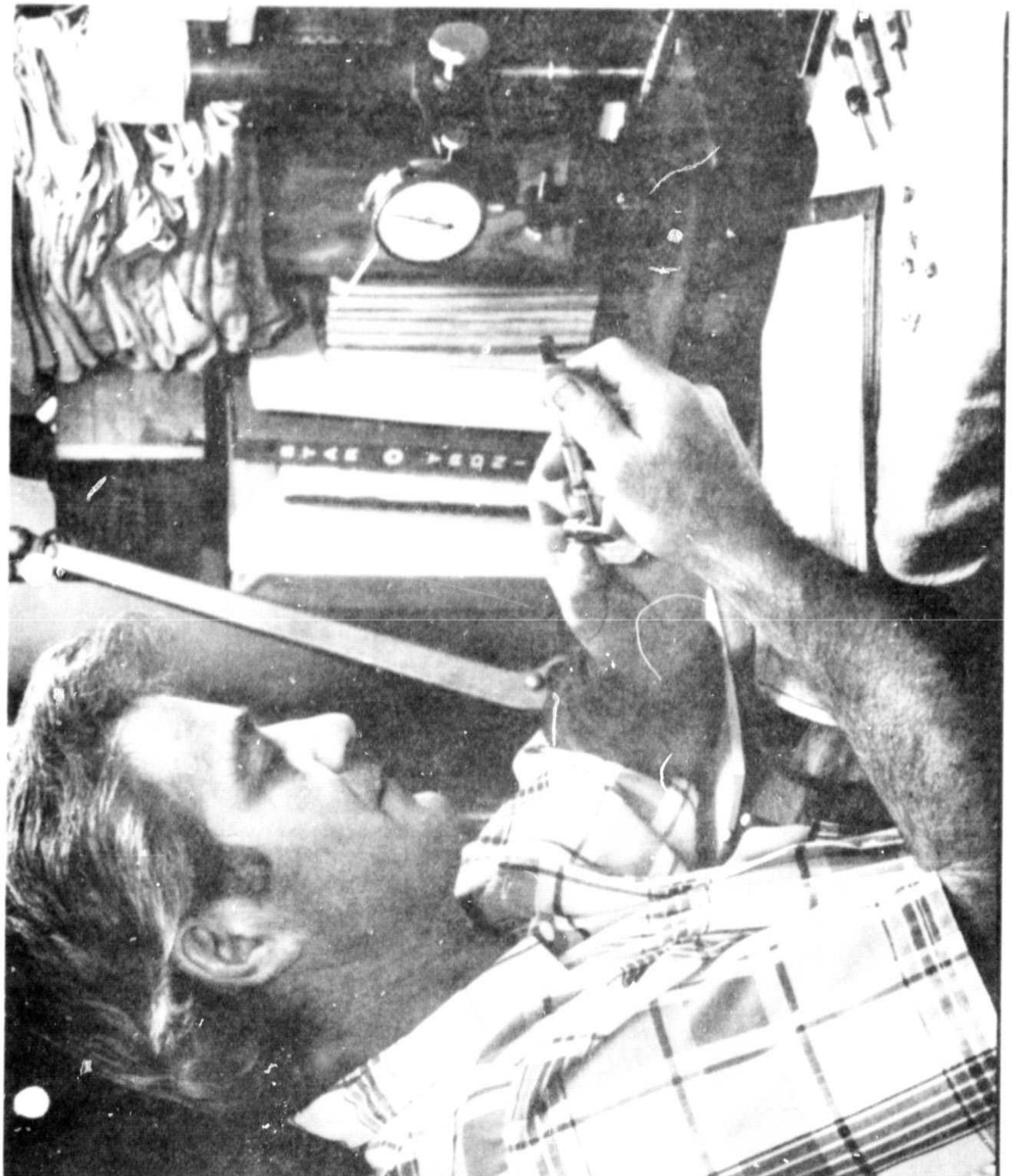

FIGURE 4-2. TYPICAL PHOTOGRAPH, AS REPRODUCED BY NPR IMAGE RECORDER

Aside from its low initial cost of approximately $8000, one of the most attractive features of the NPR is its very low operating cost. An 8 x 9.5 inch picture costs only about 1.8 cents as opposed to about 4.5 cents for dry silver paper.

The NPR is too slow for direct compatibility with any of the sensors included in this study. There may, however, be a worthwhile application for it, as discussed in 5. 3. 3.

4.5 D-700 CHARACTERISTICS

The D-700 has been produced by Muirhead Ltd. for many years and is a thoroughly proven design. It is a drum scan recorder, using a crater lamp, and records on either conventional photographic paper or film. It was chosen some years ago by Hughes for the NOAA operational ground equipment for the ATS spin scan system. Personnel at NOAA were so pleased with the D-700 that they ordered more for other applications, and are now buying them in quantity under the designation M-112 despite the drawback that this recorder requires manual film loading and processing.

The D-700 has also been used very successfully in the Hughes-designed VPIR bench test equipment for the MSS.

In many ways and certainly for its price, the D-700 is a remarkable image recorder. As discussed in 3. 3. 5 under Crater Lamps, the D-700 records with a sharply defined rectangular spot, and the resulting image quality is extraordinarily good. At one time at Hughes, the optical system of a D-700 was very carefully focused and the aperture width narrowed to produce recordings of 8000 pixels per line, an accomplishment far beyond the instrument's specified capability. The point important to this discussion is that even at that resolution, there was no visible line grouping, proving that the recorder is capable of very precise frame scan.

It should be noted that the electronics package normally supplied with the D-700 is designed primarily for wire line photofacsimile work and is an old design using vacuum tubes. For space system applications, it has been found best to buy only the D-700 mechanism and build modern transistorized electronics for it. This presents no great problem.

The D-700 is too slow for direct compatibility with any of the sensors included in this study, but, as discussed in 5. 3. 2, there may be at least an interim application for it in connection with the CZCS.

5. SENSOR/RECORDER COMPATIBILITY STUDY

A comparison of the sensor characteristics, as set forth in Table 2-1, with the image recorder characteristics listed in Table 4-2 shows immediately that the only recorder capable of handling the output of the Thematic Mapper (19,200 lines per minute at 8800 IGFOV per line) and the HRPI (39,960 lines per minute at 4000 IGFOV per line) is the LR-72. This recorder would also be compatible with all the other sensors, but it would be far from cost effective if used with any of the low speed sensors.

At the low performance end of the sensor listing is the VHRR. Its needs could be met by either the VHRR-FAX (which was developed specifically for that purpose), the LR-73 (see subsection 7.2), or the improved Laserphoto (see subsection 4.3).

Further comparison brings to light the fact that the LR-73 is capable of meeting the speed and resolution requirements of all the sensors, except the Thematic Mapper and HRPI which require the LR-72. The LR-73 thus seems like the perfect choice for a versatile image recorder, except for one possible problem which will be discussed in the following paragraphs.

5.1 MULTISPECTRAL RECORDING

For many of the applications for which the recorded imagery from multispectral sensors is used, there is a requirement that the images corresponding to the various spectral bands register with each other with an accuracy of a fraction of a picture element. This places severe demands on the scanning accuracy of the image recorder. If all the images are made on the same recorder by first storing the data on tape and rerunning the tape for each recording, then the requirement becomes one of repeatability rather than absolute accuracy.

Since the existing image recorders were designed without this requirement in mind, there is, most unfortunately, no data available as to how well they will perform in this respect.

In general, the scan of drum recorders tends to be highly repeatable, but the only multispectral sensor falling within the speed range of drum recorders is the CZCS.

As discussed in 3.3.4, the scan of a galvanometer can be made linear and precise by adding an optical clock generator and using the pulses generated by it to read the data out of the storage buffer. The application of this technique can ensure image registration along the scan line, but leaves wide open the question of registration in the dimension of frame scan.

This problem has been discussed with the various image recorder manufacturers, and their position in every case has been that testing and possible refinement of frame scan drives will be required. As mentioned in 4.2, RCA intends to conduct such tests on the LR-73 in the near future.

5.2 SELECTION OF A VERSATILE IMAGE RECORDER

For purposes of the VDHS Study, it is assumed that the results of the investigation of the LR-73 frame scan precision will be positive. It is also assumed that the LR-73 will go into production and become available at somewhere near its target price of $10,000, including electronics. On this basis, the LR-73 is selected as the versatile image recorder, suitable for use with the VHRR, the AVHRR, the CZCS, the MSS, and the improved MSS.

As stated above, the LR-72 is the only presently known image recorder compatible with the Thematic Mapper and the HRPI.

5.3 LIMITED APPLICATION IMAGE RECORDERS

During the course of this study, various special applications of image recorders to sensor systems have been considered. Some of them appear to have enough merit to be worth reporting and will be described in the following paragraphs.

5.3.1 Improved Laserphoto

As discussed in 4.3, the production Laserphoto can quite readily be modified to operate at 2400 lines per minute with resolution of 2200 pixels per line. These parameters are compatible with the CZCS. With further modification, the resolution can be improved to 4000 pixels per line which would make it compatible with the VHRR and AVHRR.

For multispectral recording, the problem discussed in 5.1 must be faced; however at this time, there seems to be no reason to believe that the frame scan of this recorder cannot be made sufficiently precise to make it suitable for multispectral use.

In any case, the Laserphoto with no changes other than the improved speed and resolution just mentioned should be very satisfactory for VHRR and AVHRR use. The fact that the basic instrument is already in volume production is an obvious advantage.

5.3.2 D-700

As discussed in 4.5, the D-700 image recorder has proven to be an excellent instrument. The fact that it is a very precisely made drum recorder means that the scan geometry tends to be very repeatable. It is likely that an optical clock generator would have to be added to the drum drive for multispectral recording, but this can be done if the demand warrants it. The point important to this discussion is that the frame scan has been demonstrated to be precise far beyond the requirements of the CZCS, and it is certainly repeatable. Since the frame scan precision of the new galvanometer scan recorders is unknown at this time, the D-700 should be kept in mind as a possible interim recorder for the CZCS, despite its limitations.

One of the limitations of the D-700 as a recorder for use in the CZCS system is that its maximum speed is 240 lines per minute, whereas the speed of the CZCS is 480. This discrepancy can be reconciled by playing back the digital data tape at one-half the speed at which it was recorded. The only drawback to this approach is that it doubles the time required for image processing, but while this might be unacceptable operationally, it might be perfectly satisfactory during bench testing and integration testing of the sensor.

A second disadvantage of the D-700 is that it requires manual loading and processing of the film. Again, this might be acceptable during bench and integration testing.

5.3.3 NPR

As discussed in 4.4, the NPR is a nonphotographic recorder which is at this time going into mass production and which is capable of producing very good imagery economically, but at a maximum speed of 200 lines per minute. Its scan mechanism is not inherently precise enough to allow its use for multispectral recording; however, it is more than adequate for producing good quality cloud pictures for visual interpretation.

Because the operating costs of the NPR are exceptionally low, and because it is slated to become a high-volume production recorder designed for reliable routine use, it is suggested that it might be applied in low budget ground stations for VHRR and single band AVHRR reception. Used in this manner, its low speed would require that it record only every second picture element and every other line. This would produce pictures having only 1.0 mile resolution rather than the 0.5 mile resolution of which the VHRR and AVHRR are capable. The pictures would, however, be much better, both as to resolution and as to gray scale, than the best pictures produced by the APT (automatic picture transmission) system, and might find wide acceptance.

6. MODIFICATION STUDY

Throughout the VDHS Study, the possibility of modifying the various image recorders under investigation, or adding peripheral equipment, to achieve sensor compatibility has been kept constantly in mind. Such possibilities have been discussed with the recorder manufacturers, and the results of these investigations are discussed throughout Section 4 and 5 of this report. To summarize, the modifications applicable to the recorders recommended for consideration by the Sensor/Recorder Compatibility Study (Section 5) are as follows.

6.1 LR-73 MODIFICATIONS

1) The resolution of the basic LR-73 can be increased from 2200 to approximately 4000 pixels per line through the addition of field-flattening optics, at a cost increase of several thousand dollars.

2) An optical clock pulse generator can be added, if necessary, to ensure registration of multispectral recordings in the line scan dimension.

3) The adequacy of the present film drive, as it relates to the registration of multispectral recordings in the frame scan dimension, is unknown. If it is found on investigation not to be adequate, it is assumed that it can be made so through modification, at an unknown increase in cost.

4) The basic LR-73 can be converted from dry silver film to dry silver paper operation for systems where paper may be preferred, such as the VHRR.

5) Digital gray scale linearity compensation can be added externally for applications where the LR-73 linearity correction is considered inadequate.

6.2 LASERPHOTO MODIFICATIONS

1) Radiation, Inc. has already offered for sale for police work, an improved version of the production Laserphoto. These improvements increase the scanning speed from 160 to 2400 lines per minute and increase the resolution from 1280 to 2200 pixels per line. It has been stated that the resolution can be further increased to 4000 pixels per line without any great difficulty.

2) An optical clock pulse generator can be added to ensure registration of multispectral recordings in the scan line dimension.

3) The adequacy of the present film drive as it relates to the registration of multispectral recordings in the frame scan dimension is unknown at this time. If it is found on investigation not to be adequate, it may well be possible that it can be made so through modification, at an unknown increase in cost.

4) The Laserphoto can be converted from dry silver paper to dry silver film operation, but it may require the use of a different type of thermal processor, as discussed in 3.7.3 and 4.3.

5) Digital gray scale linearity compensation can be added externally for applications where the Laserphoto linearity correction is considered inadequate.

6) Digital buffering can be added externally to achieve compatibility with the duty cycle of the incoming data, and also to allow the use of the optically generated readout clock mentioned previously.

6.3 NPR MODIFICATIONS

1) The speed of the production NPR can be increased from 120 to 200 lines per minute without great difficulty.

2) External electronics can quite easily be added to allow the NPR to record VHRR or single band AVHRR imagery at half speed and half resolution.

6.4 D-700 MODIFICATIONS

1) Modern drum drive and video electronics can easily be added to the basic D-700 mechanism.

2) An optical clock pulse generator can be added to the drum drive to ensure registration of multispectral recordings in the line scan dimension.

3) Digital gray scale linearity compensation can be added externally.

4) Digital buffering can be added externally to achieve compatibility with the duty cycle of the incoming data, and to allow the use of the optically generated readout clock.

7. MODULARIZATION STUDY

The LR-73 is recommended by the VDHS Study for use as a versatile image recorder. It lends itself well to modularized improvements for use with various sensors as discussed in 4.2 and 5.2. The recommended modularized improvements are as follows:

MOD 1 — Change from dry silver film to dry silver paper.

MOD 2 — Add field-flattening optics for increased resolution.

MOD 3 — Add optical readout clock and improved film drive (if necessary) for multispectral recording.

The applicability of these three modularized additions to the various sensors is then as shown in Table 7-1.

TABLE 7-1. LR 73 MODULARIZATION

Sensor	MOD 1	MOD 2	MOD 3
VHRR	X	X	
AVHRR - Single band	X	X	
AVHRR – Multispectral		X	X
CZCS			X
MSS		X	X
Improved MSS			X

8. COMPLETE SYSTEM CONSIDERATION

The purpose of this portion of the VDHS Study is to show by example and analysis how the results of the previous portions of the study can result in a cost effective data processing and image recording system for a sensor designated by the Technical Officer. The sensor which was designated for such consideration is the CZCS. The characteristics of the CZCS which impact on the design of the image processing and recording system are as shown in Table 8-1.

8.1 SELECTION OF IMAGE RECORDER

The requirements summarized in Table 8-1 are not particularly demanding as to either recording speed or resolution, and could be met inexpensively by either the high speed version of the MRCR-2, the improved Laserphoto, or the LR-73; and by recording at half-speed, as discussed in 8.2, the D-700 could also be made compatible. There is, however, the additional requirement for multispectral registration, as discussed in 5.1, and this is more troublesome.

TABLE 8 1. CZCS PARAMETERS

Number of spectral bands	6
Samples/line	2025
Scan frequency	8 lines/sec
Scan efficiency	22.3%
Total scan period	125 ms
Active scan period	27.85 ms
Sample period	13.75 μsec
Active word rate	72,730 word/sec/band
Bits/word	8
Active bit rate	581,840 bits/sec/band

Since the CZCS is a multispectral system, it is assumed that the imagery will be wanted in the form of transparencies rather than on paper. This rules out the MRCR-2 which uses stabilization paper and is not well suited to conversion to film operation.

The improved Laserphoto and the LR-73 are both flatbed galvanometer scan recorders, and registration along the scan line can be assured by using an optical clock pulse generator, as discussed in 3.3.4. This leaves the question of registration in the frame scan dimension, as discussed in 5.1. It can hopefully be assumed that this problem will be solved for either or both the LR-73 and the Laserphoto.

As discussed in 4.5 and 5.3.2, the D-700 is the only inexpensive applicable image recorder which is definitely known not to have a frame scan problem. With the addition of an optical clock generator to the drum drive, and by operating at half-speed (subsection 8.2), the D-700 can be made compatible with the CZCS system, and should be considered at least as an alternate choice at this time.

The complete CZCS system design described in the following sections is based on the use of either the LR-73, the improved Laserphoto, or the modified D-700, and is compatible with all three at the block diagram level; however, note that if the LR-73 were to be the final choice, the Digital Processing System described in 8.3 could be greatly simplified by eliminating the data buffer since the basic LR-73 includes its own data buffer.

8.2 TAPE RECORDER

Since the CZCS is a multispectral sensor, multispectral recording is required. This can be accomplished in one of three ways:

1) By using an image recorder capable of recording all six spectral bands simultaneously in real time

2) By using six image recorders whose output imagery is sufficiently precise geometrically so that the imagery from one recorder will register with the others to within a fraction of a picture element

3) By recording all the incoming data digitally in real time, and producing the output imagery by playing back the data six times through the same image recorder

The last approach appears to be the most cost effective of the three, because the tape recorder costs less than either the large and precise image recorder required by the first method, or the five additional image recorders required by the second method. The only disadvantage of this method appears to be that the image recording process is more time-consuming than it would be if it could be completed in real time. This may be more than offset by the following advantages:

1) The digital tape can, if desired, be stored for future use.

2) Multiple sets of imagery can be run from the same tape, each with different gray scale compensation to emphasize certain radiance levels.

3) If final selection of the image recorder for some or all of the recording facilities results in the choice of a recorder lacking the speed capability of recording the data at the real time rate, the tape can be played back at half-speed. On the other hand, if the image recorder chosen has excess speed capability, the tape can be played back at two or four times the recording speed, and operating time saved accordingly.

4) In the event that something should go wrong in the image recording operation, the data would not be lost.

For these reasons, a tape recorder has been incorporated in the suggested system.

The data rate, as given by the CZCS specification, is 2025 8-bit words in 27.85 ms per spectral band. This is equal to 581,840 bits per second per channel. It is recommended that the data for each spectral band be recorded on a separate tape track. Thus, a recording speed of 30 inches per second will result in a bit density on the tape of 19,394 bits per inch, which is acceptable for low error-rate recording using Miller code (narrow band phase encoding).

Since a seven track configuration is standard for instrumentation tape recorders and there are six tracks of image data, there is one track left for the line sync signal plus a frame-start code and any auxiliary data which may be desired.

The tape recorder recommended at this time is an Ampex FR2000-A having six tracks of Miller code electronics for recording and reproducing 582 K-bits per second at 30 inches per second, one high resolution analog track, and an "edge track" for voice annotation. With ferrite (long life) heads, the price of this instrument is approximately $30,000.

One of the advantages of Miller code recording is that the Miller decoders automatically generate bit-synchronous clocks for each track of data, and these clocks can be used externally for timing in the digital processing system.

8.3 DIGITAL PROCESSING SYSTEM

This subsection summarizes a study of the digital electronics needed for the processing of the Coastal Zone Color Scanner (CZCS) imagery.

The CZCS produces six spectral bands in digital multiplexed form. This data is recorded on the ground by a tape recorder, along with a line sync signal. The clocks for each band are derived from the Miller-encoded data. Only one of the six bands is selected at a time for processing. The data from the selected band is digitally processed and converted to an analog signal which drives an image recorder.

The digital processing can be implemented in many ways using different types of hardware. This report discusses several of the more practical approaches with emphasis given to the selection of memory storage devices.

8.3.1 System Parameters

Table 8-1 specifies the data format to be handled by the digital processing system.

Input from Tape Recorder

There are six data lines, one for each spectral band, the data on each line being in serial format, 8-bits per word. There are six clock lines, each bit-synchronous with its corresponding data line; and there is also a line sync signal to indicate the start of each line of incoming data.

Input from Image Recorder

A readout clock is generated by the image recorder and used in the digital processing system to time the video output to the image recorder. This eliminates any possibility of geometrical distortion of the image due to nonlinearity of the image recorder line scan.

Output to Image Recorder

The principal output to the image recorder is the analog voltage (video) which controls the modulated light source in the image recorder and determines the instantaneous density of the recorded image. There is also a line sync signal sent to the image recorder to synchronize the start of each scanning line.

Processing Requirements

The digital processing system must provide for the manual selection of any one of the six incoming data lines, with its corresponding clock. It must perform a serial to parallel conversion and store all of the 2025 8-bit data words. Circuitry must be provided to perform linearity correction. The shape of the linearity correction curve is determined by operator inputs. The output of the linearity correction circuitry is a function of the correction curve and each 8-bit data word. The processed data word is then converted to an analog voltage to drive the image recording device.

Data must be accepted and stored at the incoming word rate. The processed data must go to the digital-to-analog (D/A) converter at a word rate determined by the image recording device. This necessitates the line storage.

Image recording may be done during the nonactive input data period of each line.

8.3.2 Functional Description

Figure 8-1 shows the basic block diagram suggested for hardware implementation of the digital electronics subsystem.

The operator manually selects the data and clock lines of one of the six spectral bands coming from the tape recorder.

The selected data and clock lines and the LINE SYNC signal are buffered to provide good noise immunity and signal voltage compatibility.

A serial to parallel conversion is accomplished through the use of a serial input/parallel output 8-bit shift register integrated circuit.

A linearity correction is performed on each 8-bit input data word. The incoming data rate is fixed, allowing ample time to perform the linearity correction prior to storage. The amount of correction is determined by operator input which is stored in a random access memory (RAM). The 8-bit input data word addresses the output data word stored in the RAM. Methods of inputting and storing the linearity correction data are discussed in more detail in 8.3.3.

The output data from the linearity correction circuit are stored in a 2048 by 8-bit data buffer during the input data cycle of each line. There are many different memory devices available for implementing this storage. They are discussed further in 8.3.4.

After a complete line of data is stored in the memory, the output data is read into an 8-bit parallel buffer register. The register output drives a D/A converter. The buffer register makes possible the synchronization of the video signal with the image recorder, and also eliminates the delay of the line storage read cycle from the readout clock timing. The output data rate is determined by the image recorder clock signal.

Most digital-to-analog converters introduce some noise and ringing or overshoot and undershoot when changing steps. This can be eliminated by a simple low pass filter if necessary.

Actual implementation of the timing circuitry will depend on the devices used for line storage. Almost all devices will require a 3-bit counter for serial to parallel conversion and an 11-bit counter for keeping track of the number of incoming data words for each line.

8.3.3 Gray Scale Linearity Compensation

For this design, digital gray scale compensation through the use of a random access memory (RAM), as discussed in 3.6, has been chosen. The advantages of this system are operating flexibility and ease of implementation. The hardware required to accomplish this consists essentially of a 256 word by 8-bit RAM, and circuitry and controls for loading the desired compensation data into the RAM.

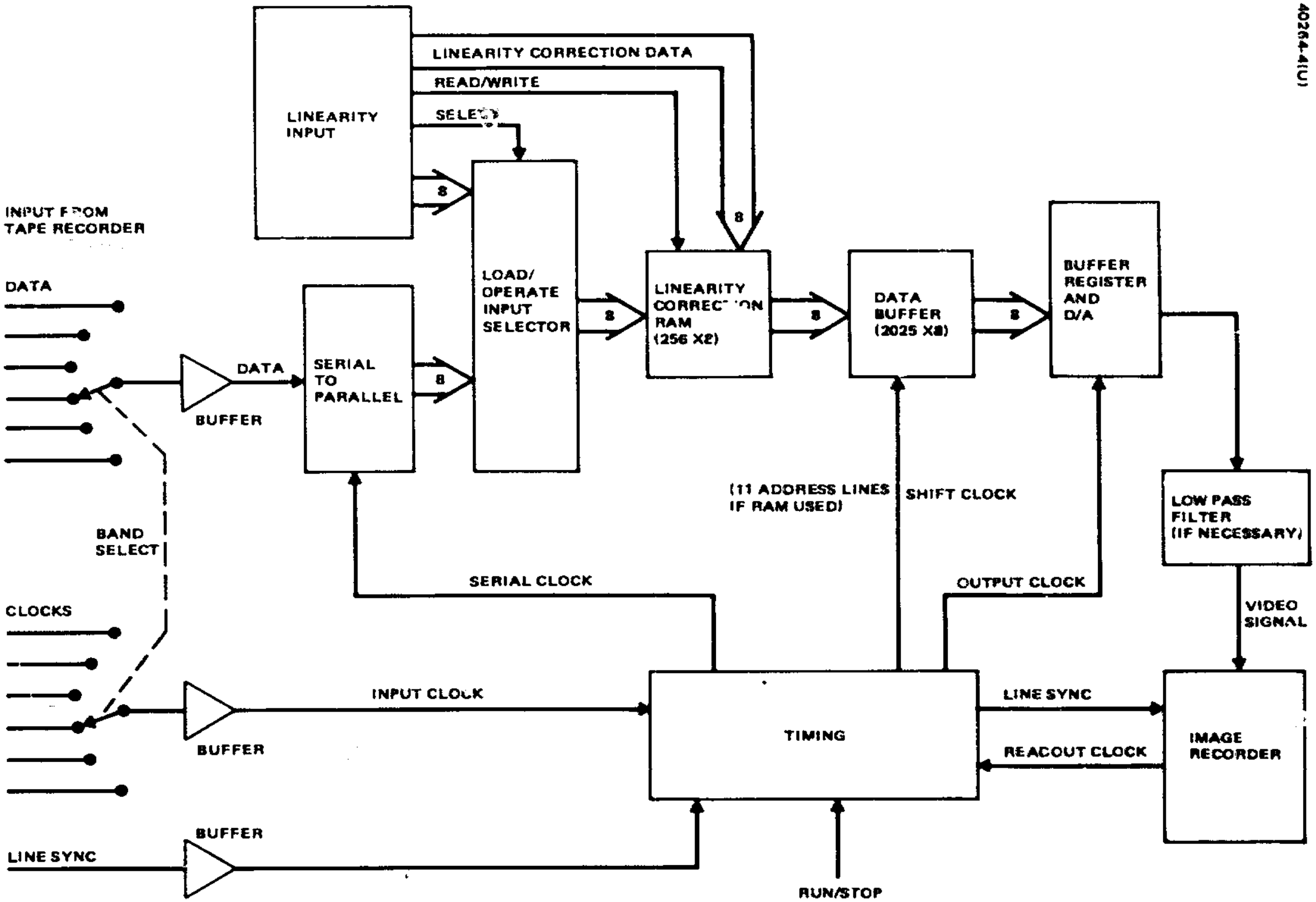

FIGURE 8-1. DIGITAL ELECTRONICS SUBSYSTEM BLOCK DIAGRAM

8.3.3.1 Choice of [illegible] Scale Compensation Memory

In selecting the type of memory device to be used, cost, ease of incorporation into the design, and nonvolatility are prime considerations. The need for nonvolatile storage arises from the fact that if a volatile memory were to be used, the compensation data would be lost whenever a power interruption occurred. Nonvolatility can be provided either by choosing an inherently nonvolatile type of RAM, or by providing a standby battery supply to the RAM which will ensure uninterrupted memory operation. If a RAM having a very low input power requirement, such as a metal oxide semiconductor (MOS) device, is chosen, the standby battery requirement becomes almost trivial.

There are presently available four basic types of devices which can be used to build a 256 by 8-bit random access memory. Table 8-2 summarizes the characteristics which are significant in selection of the type most suitable for this application.

The core memory provides inherent nonvolatility; however, certain timing and power-off procedures must be observed to protect the stored data, and the power requirement is the highest of any of the memory types.

MOS RAMs are available with very low power drain during the stand-by mode, so that a backup battery power system can be implemented easily to provide standby power to the MOS memories during unit power-off. A standby power source is not conveniently implemented for bipolar memories.

TABLE 8-2. CHARACTERISTICS OF CURRENTLY AVAILABLE RAM DEVICES

Type of Memory	Nonvolatile	Timing Interface	Read Cycle Time	Package Array	Packaging	Cost for 256 x 8 Array (Hardware Only), dollars
Core	Yes	Requires read/ refresh each word cycle	9.6 μsec	2048 x 1	PC card	500
Static MOD RAM	No	Convenient	1 μsec 4 μsec	256 x 1 1024 x 1	DIP	<100
Bipolar RAM	No	Convenient	25 to 100 ns 240 to 400 ns	256 x 1	DIP	400
Dynamic MOS RAM	No	Noise suscepti- bility requires periodic refresh cycle	1 μsec 8 μsec	256 x 1 2048 x 1	DIP	<100

Most memories do not come in convenient 256 x 8-bit arrays. Rather, they come in long single bit configurations, unless an entire memory system is procured. Since dual in-line packaging is compatible with most MSI/LSI integrated circuits, building up the 256 x 8 memory out of single bit arrays is still cost effective. Eight 256 x 1 arrays can be combined in parallel to provide the full memory without sacrifice in speed.

Memory speed is a consideration in design implementation only to the extent that each incoming data word must be processed and stored in the output memory circuit within the 13 μsec of each word period. All four device types are fast enough, though more care in overall system timing will be necessary with the slower configurations.

All four memory devices are generally available with all interface, decoding, and timing circuitry built in. Most products are fully TTL compatible, including the MOS devices. This is convenient since most logic designs of this speed are implemented using SSI and MSI TTL integrated circuits.

All four devices are reasonably easy to design into a system although the core memory requires some additional timing circuitry to retain memory data during a read cycle, and the dynamic RAM requires periodic refresh cycles to prevent data loss. More careful consideration must be given to the dynamic RAM interface to avoid problems due to noise susceptibility.

One other memory device should be mentioned, although it is not yet available as a fully decoded memory. It is the electrically alterable read only memory (EAROM). The most suitable device for this application is the Amorphous Semiconductor EAROM. This device offers the capability of reprogramming with nonvolatility. It is presently available as a monolithic array but does not contain the interface and decoding circuitry necessary for its use in a system. When it is commercially available as a fully decoded, integrated memory, it will become a desirable alternative.

8.3.3.2 Methods for Entering Linearity Compensation Data

Three possible approaches to loading the linearity compensation data into the memory are discussed in this section. They are:

1) Use of a paper tape reader

2) Manual front panel operation

3) A combination of manual and paper tape operation

Paper Tape Method

In the paper tape method, the desired output signal level corresponding to each of the 256 possible input levels is stored by the operator on

punched paper tape. This necessitates the availability of a tape punching facility, such as a teletype. To store the data in the linearity compensation RAM, the tape is run through a standard tape reader that must be supplied as part of the system. The principal advantage of this approach is that a number of tapes can be kept on hand, with different compensation curves for different situations, and whenever it is desired to record imagery with a special gray scale, the corresponding compensation tape can quickly be run. A secondary advantage is that a volatile memory can then be used, since the tape could be rerun after any power outage; but since a nonvolatile memory is not expensive, this is not an important point.

Figure 8-2 shows a block diagram of one possible implementation of the tape operation. Several convenience features are incorporated at little expense.

A tape identification number can be punched first. This number may be displayed on the front panel to give visual indication of the data stored in the memory. Each tape of data would have a unique identifying number. An added feature would blank the display whenever power is cycled or memory voltage dropped. The display would remain blank until a tape is reloaded.

The second tape entry selects the starting address. Each succeeding tape entry is data which is stored in successive RAM locations starting with the specified address.

The principal disadvantage to the use of punched paper tape is the necessity for access to a tape punch machine. A secondary disadvantage is that if changing only a few points on the compensation curve is desired, an entire new tape must be prepared.

Manual Data Entry

Since it is not known at this time whether or not it can be assumed that tape punches will be available at the various CZCS recording facilities, some thought has been given to the design of a manual data entry system which would be fast and convenient in operation without being expensive to implement. Such a system is described in the following paragraphs.

A sketch of the recommended manual data entry panel is shown in Figure 8-3. Experience has taught that the difference between any given output level and the preceding one is never greater than four. It will be noted that, in the sketch there is a row of pushbuttons labeled 0, 1, 2, 3, and 4. These correspond to the increment between the last output level entered into the memory and the next desired level. Each time one of these buttons is operated, the input number is increased by 1 and the corresponding output number is increased by 0, 1, 2, 3, or 4, depending on which button was pressed. The corresponding input and output numbers are shown on the decimal displays at the top of the panel. By this method, the entire memory can be loaded quickly and easily.

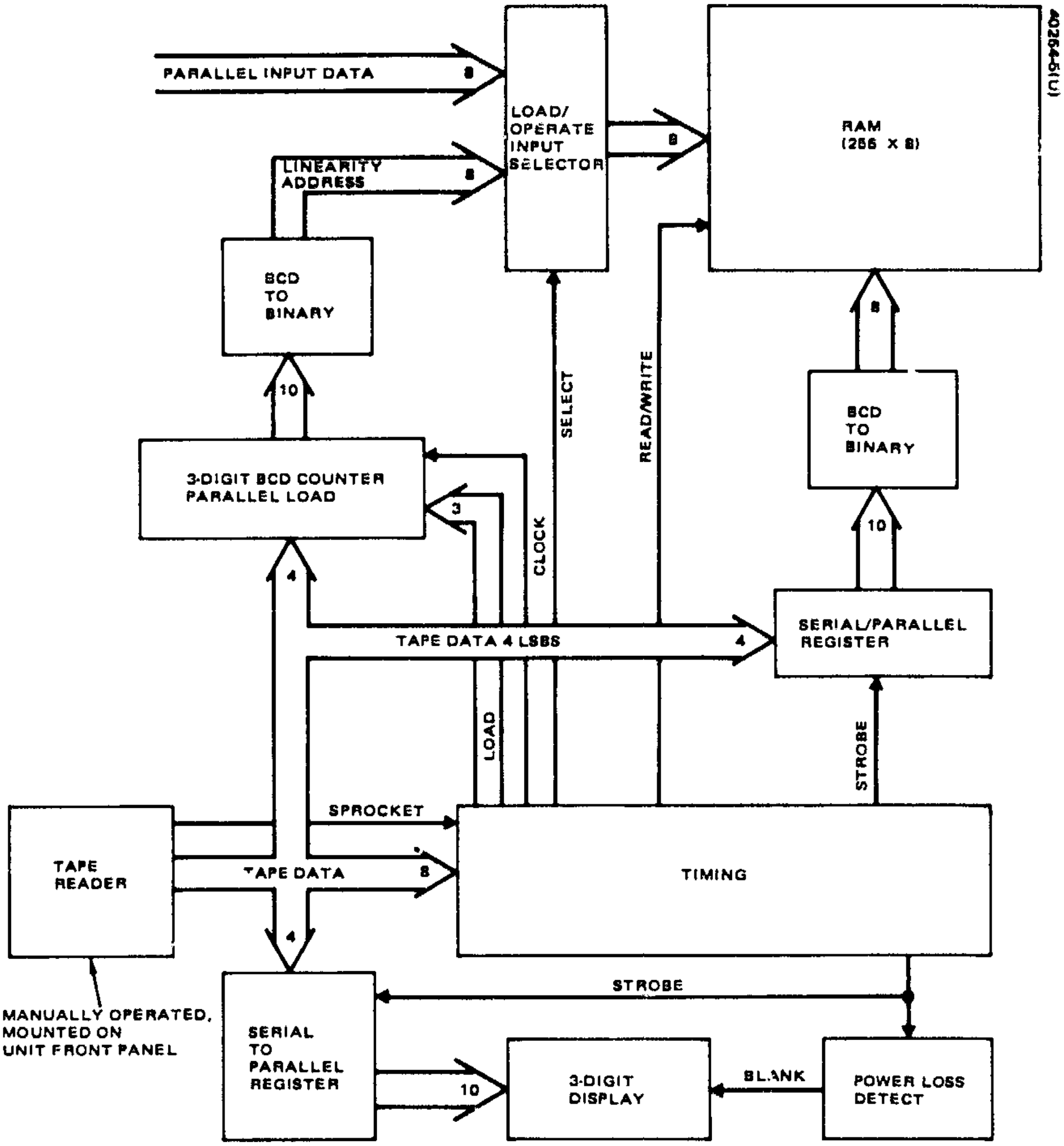

FIGURE 8-2. TAPE OPERATION LINEARITY COMPENSATION
BLOCK DIAGRAM

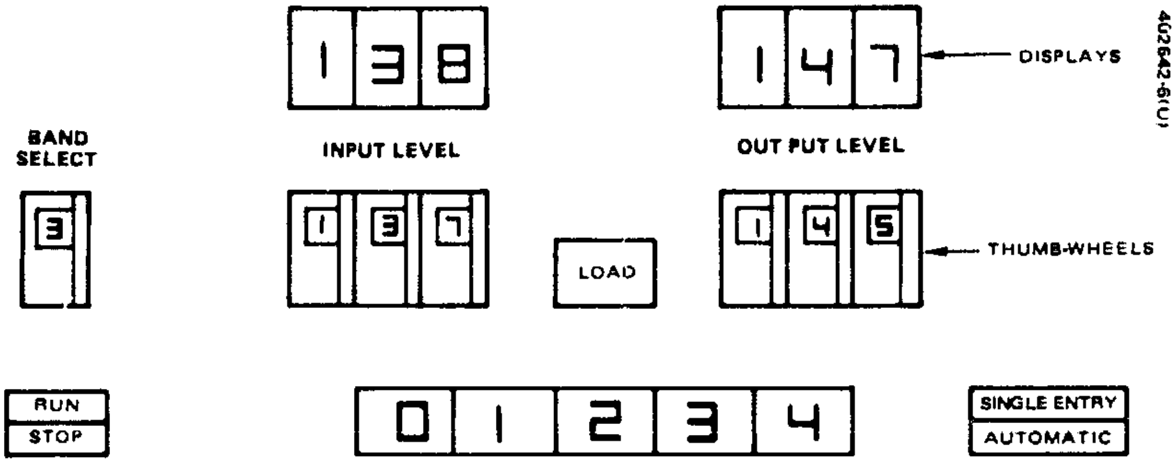

FIGURE 8-3. FRONT PANEL FOR MANUAL OPERATION
LINEARITY COMPENSATION

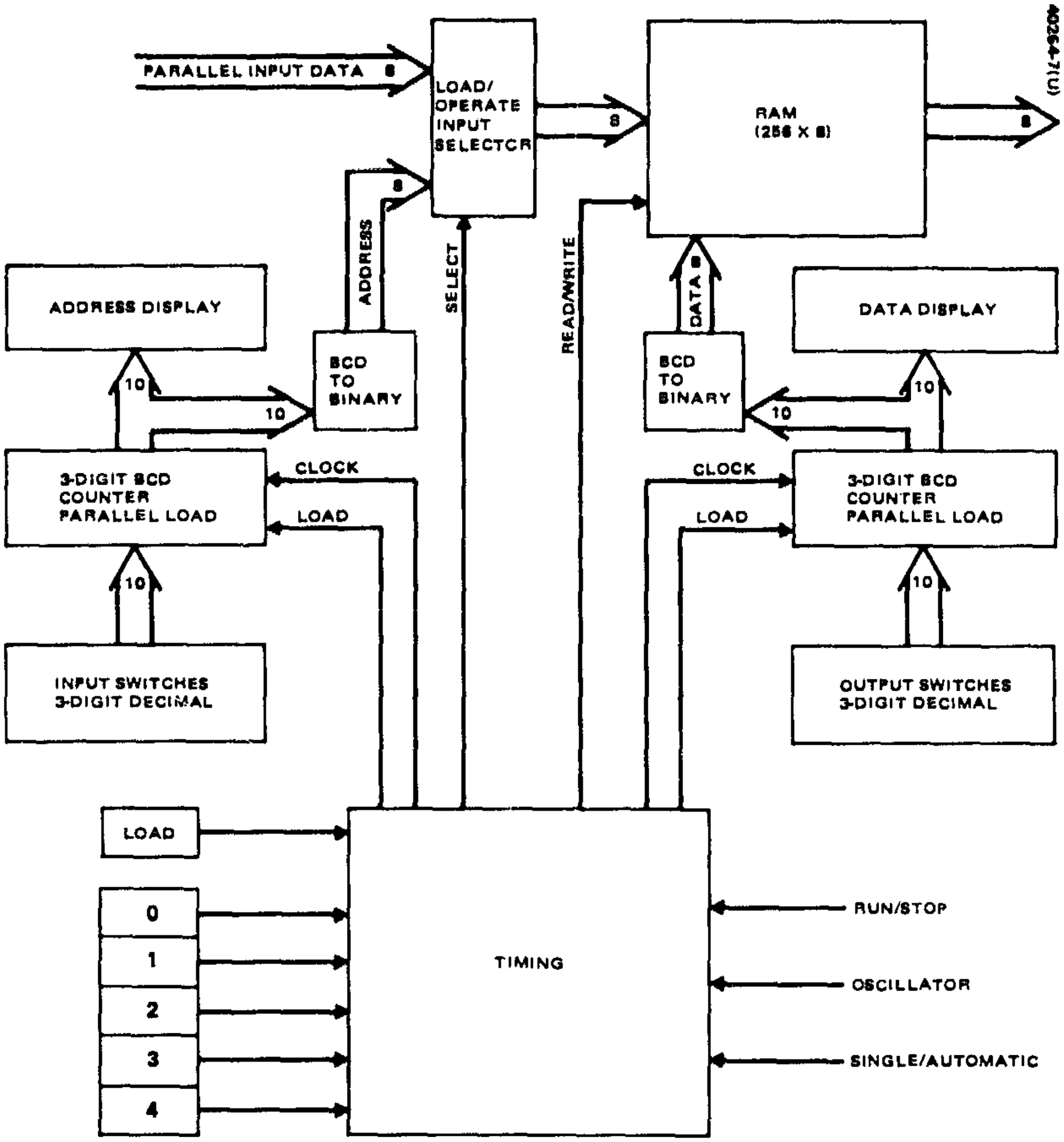

FIGURE 8-4. MANUAL OPERATION LINEARITY COMPENSATION BLOCK DIAGRAM

If changing only a few points on the compensation curve or correcting an improper entry should be desired, the system can be switched from AUTOMATIC to SINGLE ENTRY. The desired input level and corresponding output level are then set up on the decimal thumbwheel switches provided, and the LOAD button pressed.

To set the counters to zero at the start of an automatic loading sequence, the system is put in SINGLE ENTRY, the thumbwheel switches set to 000, and the LOAD button pressed. The system is then switched to AUTOMATIC and the loading sequence continued as described above.

Figure 8-4 is a block diagram showing the implementation of this concept for manual data entry.

Combined Tape and Manual Data Entry

The most flexible system for entering the linearity compensation data would combine the ability to read punched paper tape with the automatic and single entry manual capabilities described above. Since most of the electronic circuitry is shared by the three methods, the primary cost considerations are the price of the tape reader and front panel complexity.

Figure 8-5 is a block diagram showing a hybrid data entry system combining the capability of reading paper tape with single entry manual capability, but without the automatic manual operation already described. This is the approach incorporated into the recommended Digital Processing System described in 8.3.6.

8.3.4 Selection of Memory for Data Buffer

A total of 2025 8-bit words must be stored to hold a complete line of data. Table 8-3 gives several significant characteristics of seven different memory devices suitable for this application. Because the data words in each line do not have to be randomly accessed, shift registers and first-in, first-out buffers (FIFOs) can be considered practical devices for implementation of line storage.

Each line of data need not be stored longer than one scan period of 124 ms. Thus there is no requirement for nonvolatility of the output data storage medium.

This memory size is eight times greater than that of the linearity correction RAM. All power consumption will be correspondingly increased. The core memory and FIFO device will have an order of magnitude greater power consumption than the MOS devices. The static MOS RAM will draw typically from 10 to 20 watts while the MOS dynamic RAM and MOS shift register draw typically only 2 to 5 watts for a 2K x 8 memory array.

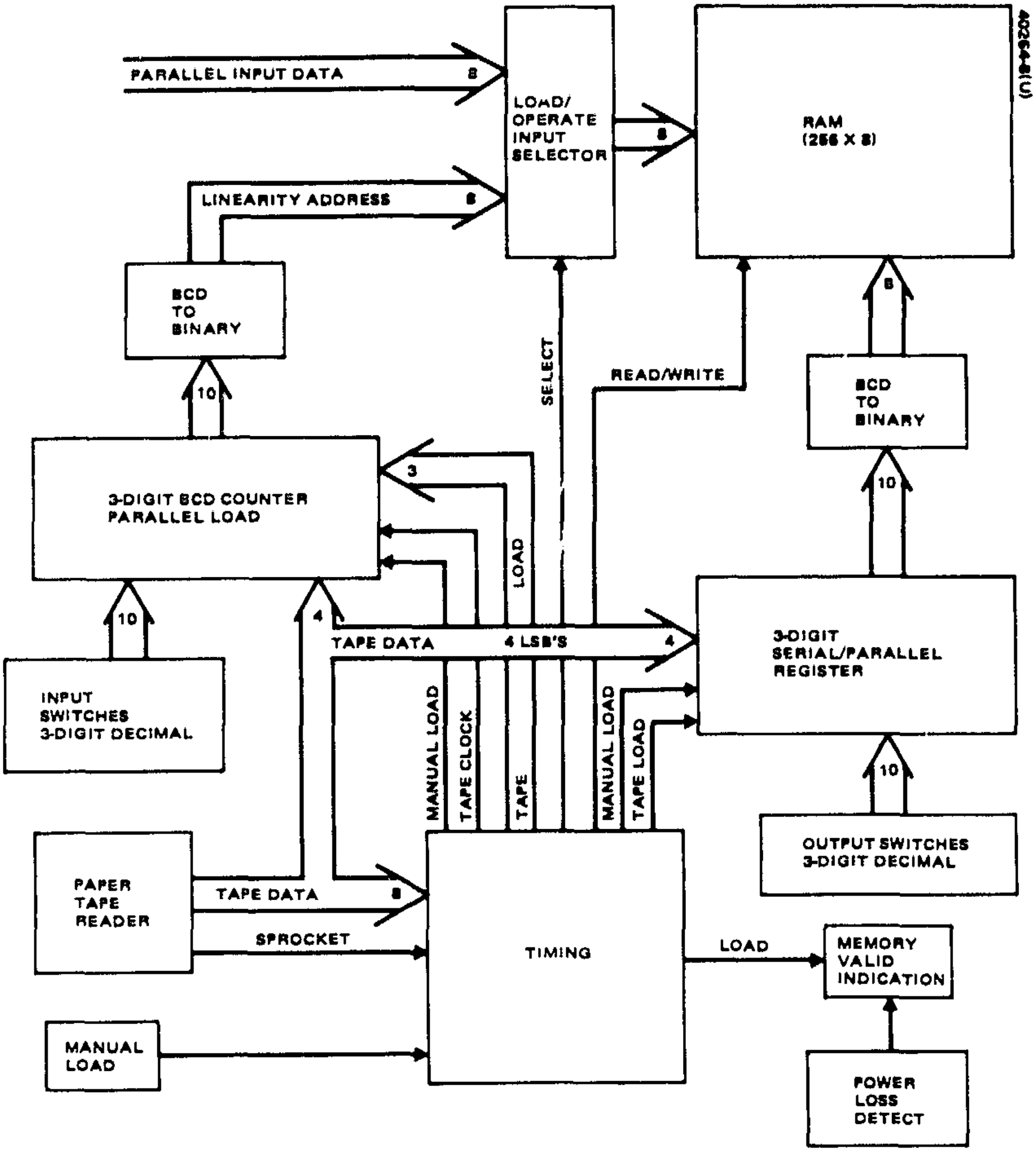

FIGURE 8-5. MANUAL AND TAPE OPERATION LINEARITY COMPENSATION

TABLE 8.3 CHARACTERISTICS OF APPLICABLE MASS MEMORY STORAGE DEVICES

Type of Memory	Timing Interface	Package	Number of Bits/Package	Number of Packages/Array	Cost for 2048 x 8 Array (Hardware Only), dollars
Core	Convenient	PC Card	8192	2	1,300
Static RAM	Convenient	DIP	1024	16	500
Dynamic RAM	Noise suscepti bility requires refresh	DIP	2048 4096	8	320 160
Static shift register (MOS)	Convenient	DIP	1024	16	250
Dynamic shift register (MOS)	Noise suscepti bility requires refresh	DIP	1024	16	160
FIFO (first in, first out)	Convenient. Allows input and output simultan eously at different rates	DIP	40 x 9	59	1,836
CCD (charge coupled device)	MIN/MAX speed requires recycle	DIP	-	-	-

The maximum output data rate capability of the digital electronics subsystem will be determined by the D/A converter speed or the readout speed of the memory storage device, whichever is slower. All the memories will operate at least as fast as most voltage output high speed digital-to-analog converters. The only memory with cycle time greater than 1 μsec is the core. Thus, all of the listed memory devices satisfy speed requirements.

All the memories except the charge-coupled device (CCD) are available with TTL compatible signals. This allows ease of design into the system without special interfacing circuitry. The dynamic MOS devices require periodic refresh cycles to prevent loss of data during the 124 ms line period. This requirement complicates the timing circuitry. The first-in first-out buffer memory provides the greatest flexibility in timing circuitry, allowing data to be clocked in and out simultaneously at different rates. The CCDs would require approximately the same timing considerations as the dynamic MOS devices. The timing requirements for the static MOS devices and the core memory are very simple.

The core memory is available on PC boards. The entire 2048 by 8-bit memory will fit on one or two boards. The other devices come in smaller array sizes in dual in-line packages. These can be combined to build up the larger memory array.

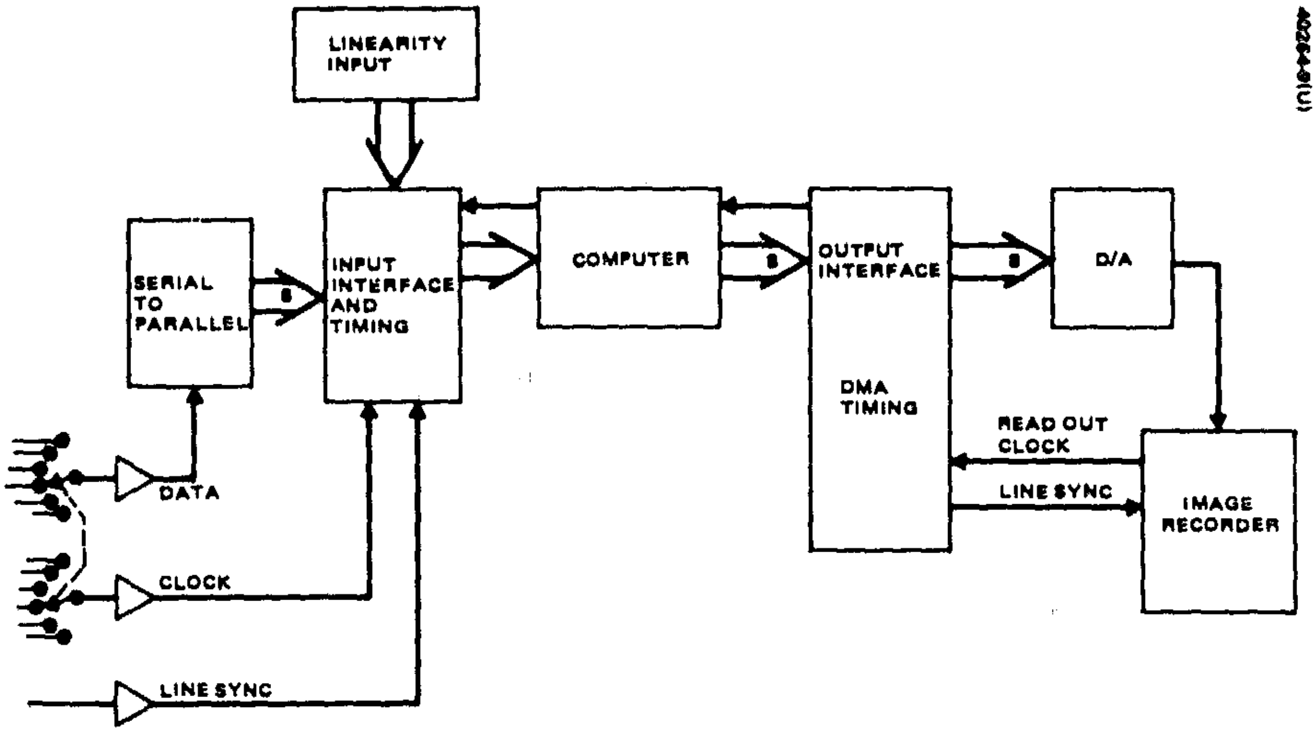

FIGURE 8-6. MINICOMPUTER IMPLEMENTATION BLOCK DIAGRAM

The RAM memories will require more interconnections per package for addressing than will the shift registers or FIFOs.

The shift registers do not come in a convenient length for exactly 2025 words. If sixteen 1024 × 1-bit arrays are used, 23 additional clocks must be inserted at the end of each active data input period to shift the first output word to the end, but, since the Miller decoders of the tape recorder provide a continuous clock source, this presents no problem.

Little has been said about the charge coupled devices thus far. These are relatively new devices which are just starting to become commercially available and are listed here for reference only. For this application, they offer no advantage over presently available shift registers.

8.3.5 Minicomputer Implementation

The feasibility of implementing the digital electronics subsystem through the use of a minicomputer has been considered and is discussed in this subsection. The possible advantage would be a reduction in hardware. Figure 8-6 shows a block diagram implementing the subsystem with a minicomputer.

The computer replaces the 256 RAM memory for the linearity compensation, the 2048 × 8-bit data buffer memory, and the 12-bit counter necessary in the timing circuitry. It also simplifies the hardware necessary for the linearity input.

The hardware/software structure must be such that the output data function from the computer is performed through a Direct Memory Access capability. This is the only way the requirement can be met that the output data rate be determined by the image recorder. If a Direct Memory Access channel is not used, the Image Recorder will at times run faster than the computer programming.

The disadvantages are that input and output interface hardware is required along with special timing circuitry. The data interfaces should be no more than buffers. The complexity of the timing interface can range from simple to complicated depending on the specific minicomputer utilized. In any case, the required timing hardware will be less than that required without a computer.

The processing done by the computer is minimal in terms of software. A simplified flow chart of the software used to process the data is shown in Table 8-4. A separate program would be required to read in linearity correction data. That program is not critical since it does not need to operate at the same time pictures are being processed.

Steps 3 through 7 of the flow chart (Table 8-4) must be accomplished within the fixed input data time period of 13.75 μsec. All steps (1 through 11) must be accomplished within the fixed scan period of 125 ms.

TABLE 8-4. INSTRUCTION FLOW FOR DATA PROCESSING

1) Initialize input parameters.
2) Wait for line sync interrupt.
3) Read data word.
4) Look up corrected data.
5) Store data in output array.
6) Check for 2025 data words.
7) If 2025, jump to step 3.
8) if 2025, continue with step 9.
9) Set up DMA output parameters.
10) Wait for DMA interrupt.
11) Jump to step 1.

The detailed instruction programming for steps 3 through 7 which processes the input data and the time it takes to execute each instruction, is shown in Table 8-5. This timing is based on the Computer Automation LSI-2 computer with a 980 ns cycle memory, which is the fastest one offered. By most standards this would be considered a fast computer.

TABLE 8-5. DETAILED INSTRUCTION PROGRAMMING OF INPUT DATA PROCESSING

Function	Instruction	Execution Time
Read input data into X	RDX	2.38 μsec
Load A indirect, indexed	LDA *@	3.14 μsec
Load X with storage pointer	LDX	2.06 μsec
Store A indirect, indexed	STA *@	3.24 μsec
Increment storage pointer check 2025?	IMS	3.94 μsec
Jump to RDX instruction	JMP	1.38 μsec
Total execution time		16.14 μsec

Minicomputer Implementation Conclusion

As can be determined from Table 8-5, the speed of a minicomputer is too slow for effective use in this application.

8.3.6 Recommended Digital Processing System

Figure 8-7 is a block diagram of the recommended implementation of the digital processing system. Hardware design should be based on the use of medium scale and large scale integrated circuits wherever possible. Selection of memory types and the method of data entry for linearity compensation is discussed next.

Choice of Memory for Linearity Compensation

The linearity compensation memory is assembled from eight 256 x 1-bit MOS static RAMs. These units are readily available and easily incorporated into the system. Their low standby power requirement makes the use of a small battery for ensured nonvolatility entirely practical.

The use of bipolar RAMs would offer no system advantages. The higher speed of the bipolar units is not needed, and the cost and power consumption would be greater.

The use of dynamic MOS RAMs would complicate the system design, and offer no significant cost advantage.

A core memory, when reconfigured for the 256 x 8 array needed here, would have an access time of nearly 10 μsec. This would eliminate any possibility of ever processing imagery at twice the normal rate by increasing the tape recorder playback speed, as discussed in 8.2. Also, because of packaging considerations, the cost of system product design would be increased.

Choice of Memory for Data Buffer

The 2048 x 8-bit data storage buffer is assembled from sixteen 1024 x 1-bit MOS static shift registers. These units are readily available and are easily incorporated into the system. Their overall cost and power consumption are competitive with all other devices, and their small size leads to the lowest overall packaging cost. If 2048 x 1 MOS static shift registers should become available, which appears quite probable, they would be used with still greater economy.

Core storage, at higher cost and greater power consumption, offers no advantage.

Since the system timing is such that there is no requirement to write into the memory while reading out, and the cost of FIFOs would be greater, their use is not justified.

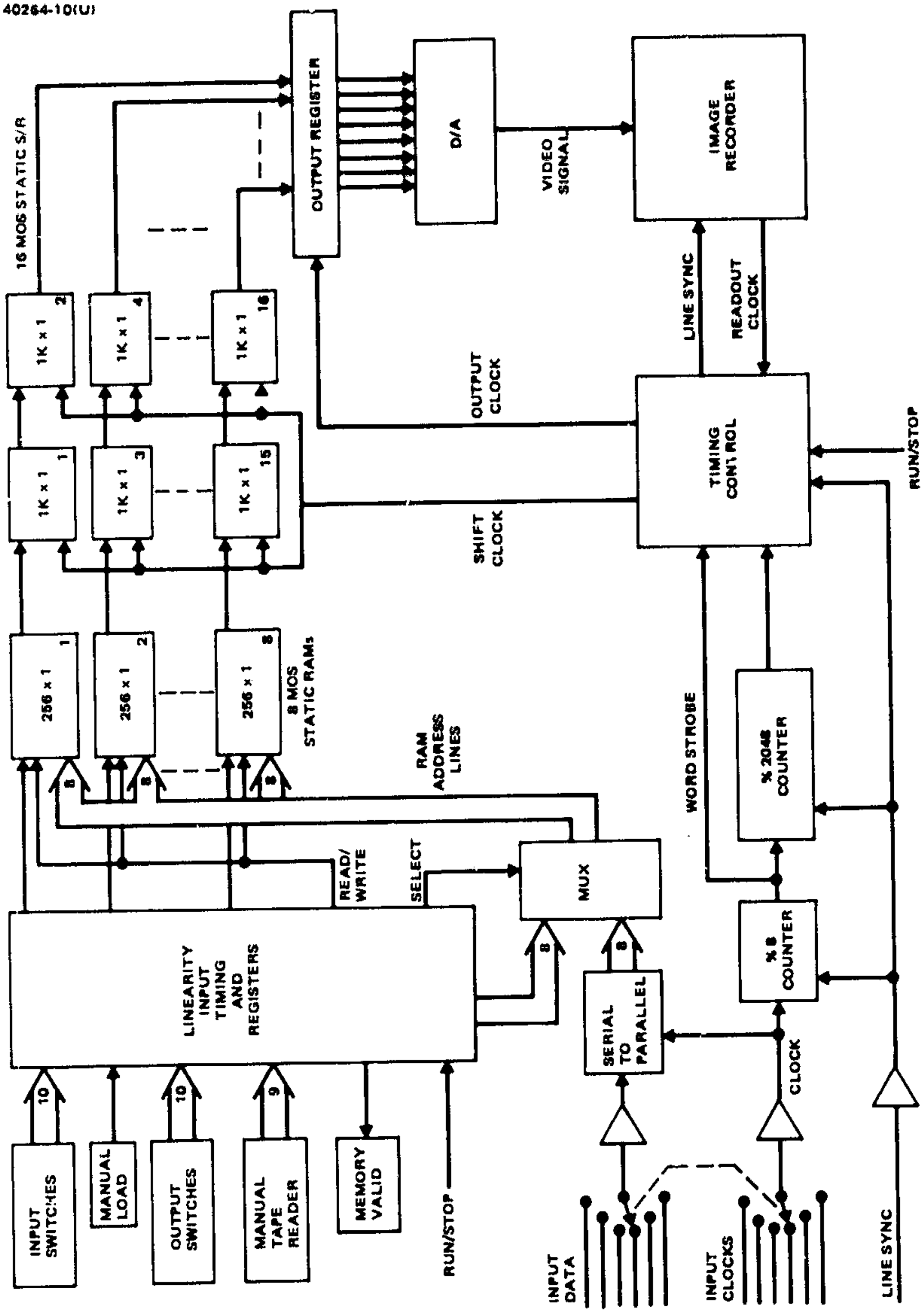

FIGURE 8-7. DIGITAL PROCESSING BLOCK DIAGRAM

The added complexity which would result from the use of dynamic MOS devices would more than offset the slightly lower cost of the devices.

Static RAMs would require more interconnections per device package, and offer no advantage.

Linearity Compensation Data Entry

The advantages of various methods of linearity compensation data entry have been discussed in 8.3.3.2. The method tentatively chosen for the system design is one which combines paper tape input with single entry manual operation without the automatic manual capability.

8.4 SYSTEM COST

The estimated cost of the basic recommended CZCS image processing and recording system is as follows:

	1 System	20 Systems
Image recorder	\$15K	\$10K
Tape recorder	30K	25K
Digital processor	45K	10K
Integration and check out	20K	1K
Total	\$110K	\$46K

9. SUMMARY AND CONCLUSIONS

1) Presently, the LR-73 image recorder, manufactured by RCA, is recommended as the most promising choice for a versatile image recorder potentially compatible with the VHRR, AVHRR, CZCS, MSS, and Improved MSS sensors.

2) The LR-72 image recorder, manufactured by RCA, appears to be the only presently available recorder compatible with the existing tentative specifications for the Thematic Mapper and the HRPI

3) Because of the rapid rate of advance in the image recording art at this time, delay of the selection of image recorders is suggested for use with sensors which are more than 2 or 3 years downstream.

4) Several limited applications for specific image recorders are discussed in this report.

5) A problem area which should be of concern at this time is the compatibility of the frame scan precision of the LR-73, and all its competitors, with the requirements of multispectral recording.

6) A possible alternative to the CZCS system discussed throughout Section 8 is described in Appendix B.

APPENDIX A

LISTING OF IMAGE RECORDING EQUIPMENT MANUFACTURERS

	Manufacturer	Comments
1)	3M Company Microfilm Products Division St. Paul, MN James W. Kugler (612) 733-2078	Manufactures dry silver film and paper.
2)	3M Company Mincom Division Camarillo, CA Robert Bradford (805) 482-1911	Manufactures EBR recorders.
3)	Addressograph-Multigraph Co. Data Systems Technology Center Cambridge, MA Burt Scudney, (617) 492-7200 Senior Staff Engineer	Has developed an automatic copier for enlarging 70 mm film negatives to 8 x 8 inch size on Ektamatic stabilization paper.
4)	AGFA-Gevaert Teterboro, NJ Robert Walsh (201) 288-4100	Manufactures the stabilization paper used in Datalog image recorders.
5)	Alden Recording Equipment Co. Westboro, MA George Stafford (617) 366-8851	Manufactures electrolytic and electrographic image recorders.
6)	Ampex Corp. Redwood City, CA Kurt Wallace (415) 367-3322	Has a limited resolution CRT raster scan recorder using the Varian model 10 electrophotographic mechanism.
7)	Ball Brothers Boulder, CO Lee Bashor (303) 441-4000	Recording on 16 mm film only.
8)	CBS Laboratories Stamford, CT Benjamin Duhov (203) 327-2000 Merle Hannah	Has developed very high performance (and high cost) laser beam recorders. Primarily a research and development facility.

Manufacturer		Comments
9) Dacom Sunnyvale, CA	(408) 734-3710	No capability in continuous tone recording.
10) Dupont Wilmington, DE	(302) 774-2421	Manufacturer of Dylux dry photographic materials. Much too slow for VDHS.
11) EDO-Western Corp. Salt Lake City, UT Robert Lapetina Howard Jones	(801) 486-7481	Manufactures CRT fiber optic line scan recorders using dry silver paper. Dynamic range, speed, and resolution all insufficient for VDHS.
12) EG&G, Inc. Bedford, MA Anthony Aponick	(617) 745-3200	Under contract to United Press to supply the next generation of photofacsimile recorders for news terminal use. Electric stylus recording on dielectric paper.
13) EMR Aerospace Sciences College Park, MD	(301) 864-6340	Formerly manufactured CRT fiber optic line scan recorders. No longer active in image recording.
14) General Scanning Watertown, MA Richard L. Hubbell	(617) 924-1010	Principal supplier of scanning galvanometers for image recorders.
15) Gestetner Corp. Yonkers, NY William Biles	(914) 968-6666	Marketing the Rudolph Hell Electronic Stencil Imager under the name Gestefax. Electrographic stylus recording. Excellent resolution, fair gray scale, 300 lines per minute
16) Gould Instruments Newton Upper Falls, MA Mike Gallant	(617) 969-6510	Image displays only. No hard copy recording.
17) Graphic Sciences Danbury, CT Anthony Barca	(203) 744-3100	Has an electrographic recorder designed for business document transmission.
18) Ilford, Inc. Paramus, NJ Robert Aldrich	(201) 265-6000	Manufactures the stabilization paper used in Muirhead automatic news service recorders.
19) Image Information, Inc. Danbury, CT Anthony DiPentima	(203) 792-0804	Developers of advanced laser beam recorders. Recently bought out by Muirhead, Inc.

Manufacturer	Comments
20) International Imaging Systems Mountain View, CA J. C. Clifford (415) 968-6137	Specializing in display systems, as opposed to hard copy recording.
21) Kodak (Eastman) Rochester, NY	Manufactures photographic products, including Ektamatic stabilization papers and processors.
22) Litton Industries Datalog Division Melville, NY ([illegible]6) 694-8300 Bernard Rosenheck David Spencer	Modifies and sells drum scan recorders manufactured by Toho Denke and Rudolph Hell. Some activity in laser recording development.
23) Litton Industries Electron Tube Division San Carlos, CA (415) 591-8411 James E. Wurtz, Senior Applications Engineer	Manufactures fiber optic and flat face cathode ray tubes.
24) Magnavox Systems Torrance, CA Roy Sturkie (213) 328-0770	Binary black and white recording only. No continuous tone. Also data compression and high speed modems.
25) Muirhead, Inc. Mountainside, NJ Ian Smith (201) 233-6010	A long standing manufacturer of high quality photofacsimile recording equipment.
26) Nashua Corp. Nashua, NH Donald F. Lynch (603) 883-7771	Manufactures Electrace electrographic paper.
27) Perkin Elmer Corp. Danbury, CT Martin Yellin (203) 744-4000	Until just recently had broad capability in both laser and CRT image recorder development. No longer active in these fields.
28) Radiation, Inc. Melbourne, FL Carmen Palermo (305) 727-4000	Manufactures the Associated Press Laserphoto. Also active in research and development of advanced laser recording techniques.
29) RCA Communications Systems Division Camden, NJ (609) 963-8000 C. R. Thompson Charles Horton	Active in the development of advanced laser recording techniques. Developers of the LR-72 and LR-73.

Manufacturer		Comments
30) Singer-Librascope Glendale, CA	(213) 244-6541	Manufactures a 22 x 28 inch recorder using Kalvar, and a laser line scan recorder using 35 mm film.
31) Singer-Link Sunnyvale, CA	(408) 732-3800	Manufactures 35 and 105 mm microfilm recorders for computer output.
32) Varian Associates Palo Alto, CA William H. Todd	(415) 493-4000	Has developed an electrophotographic copying system which can be combined with a fiber-optic CRT to create a line scan recorder. (See Ampex.)
33) Victor Graphic Systems, Inc. New York, NY	(212) 895-6357	Facsimile recorders using electrolytic paper only.
34) Visual Sciences Huntington Station, NY K. R. McConnell John Shonnard	(516) 549-4040	Development of business document facsimile systems using electric stylus recording on dielectric paper.
35) Westinghouse Aerospace and Electronic Systems Division Baltimore, MD David Coleman Robert Hubbard	(301) 765-3845 (301) 765-6538	Development of laser recorders, including manufacturing and support capability for the DRGS recorder/processor.
36) Zerith Radio Corp. Optical Systems Group Melrose Park, IL	(312) 379-7700	Manufactures acousto-optical modulators, acousto-optical beam deflectors, and lens systems.

APPENDIX B

CZCS SYSTEM - ALTERNATE APPROACH

ALTERNATE CZCS SYSTEM

In addition to the CZCS image processing and recording system described in Section 8, a second and very different design has been considered. This alternate approach has certain attractive aspects, particularly for interim or test program use, and will be described briefly in this Appendix.

Throughout this Appendix, the system described in Section 8 will be referred to as the "basic system," and the alternative configuration described herein will be referred to as the "alternate system."

Advantages of the Alternate System

The alternate system has certain advantages over the basic system. These are:

1) No tape recorder is required (although one can be used, if desired).

2) All six spectral images are recorded simultaneously in real time.

3) Precise registration of the multispectral images is more easily assured.

Disadvantages of the Alternate System

The alternate system also has certain disadvantages as compared to the basic system. These are:

1) The versatile image recorder recommended by the VDHS Study is not compatible.

2) Manual loading of the film onto the recording drum and manual darkroom processing of the film are required.

3) The format of the recorded imagery is smaller than that produced by the basic system.

ALTERNATE IMAGE RECORDER

The alternate system is based upon the use of the Muirhead K-661 image recorder listed in Table 4-2. Since no detailed description of this recorder was included in the body of the VDHS Study Report, it will be given here.

K-661 Image Recorder Characteristics

Like the D-700, the K-661 image recorder is manufactured by Muirhead, Ltd., and sold in the United States by Muirhead, Inc. It was developed for the newspaper page-facsimile market, and is a thoroughly proven design. It is a drum scan, crater lamp recorder that uses conventional film. The recording format is very large, the drum being 24 inches long and 24 inches in circumference. In newspaper work, the K-661 normally operates at 3600 lines per minute with a resolution of 1000 lines per inch.

The basic K-661 is equipped with a high-resolution optical encoder which can be used to ensure registration of imagery along the scan line, as discussed in 3. 3. 4.

At the K-661's normal operating speed of 3600 rpm and resolution of 1000 lines per inch, the crater lamp is being pushed to just about its limit; however, at the greatly reduced speed and resolution required by the alternate system (480 rpm at 480 lines per inch), crater lamps should function very well and have a more-than-satisfactory life expectancy.

K-661 Modifications

Certain modifications to the K-661 image recorder would be required to make it compatible with the alternate system. These are:

1) Since the K-661 is designed for binary black and white recording rather than continuous tone work, a video amplifier and crater lamp driver designed for continuous tone operation must be provided. This presents no problem.

2) The induction motor which drives the drum must be replaced with a synchronous motor in order to maintain line-synchronism with the incoming data if the alternate system is to operate without a tape recorder. (If a tape recorder is included in the system, then the tape recorder drive, which is servo controlled, can be servoed to the output of the K-661 optical encoder and the synchronous motor is not necessary.)

3) The lead screw of the production K-661 may have to be replaced with a more precise one to avoid visible line grouping.

4) The lead screw drive will probably require modification. The K-661 uses a step, or incremental, line-feed, each step being 0.0002 inch, so that at the normal scan density of 1000 lines per

inch, there are five steps per line. These steps actually occur at equal intervals during the scan,which for the K-661's intended application is perfectly satisfactory; however, it appears that a modification of this technique will be needed for the CZCS alternate system.

These modifications have all been discussed with Muirhead engineers, and appear feasible. No estimate of the cost has been attempted, however.

RECORDED IMAGE FORMAT

The six spectral images of the CZCS would be recorded as six parallel strips, side by side on a single sheet of film. The recorder drum would operate in synchronism with the CZCS line rate, at 480 rpm. During each revolution of the drum, the corresponding lines of all spectral bands would be recorded.

The maximum usable film width (that is, the maximum usable portion of the drum circumference) is 22 inches. For preliminary analysis, let us assume a recording scan density of 480 lines per inch, which is well within the capability of the K-661 (and by pure coincidence the same as the lines per minute). This would result in each spectral image being 3.33 inches wide, and if equally spaced across the available 22 inches, would leave a space of 0.4 inch between images, which seems about right.

At this scanning density (480 lines per inch), the length of the drum is more than sufficient to allow the continuous recording of all the imagery received during one satellite pass; in fact, preliminary calculations indicate that two consecutive passes could be recorded on a single film, if desired.

IMAGE REGISTRATION

As previously mentioned, the high resolution optical encoder provided as part of the K-661 can be used to generate a clock for reading out the data buffers, thus assuring accurate resolution of the six spectral images in the scan line dimension.

Registration in the frame scan dimension is assured by the fact that corresponding lines of the six spectral images are recorded on the same line of the recorder scan. It may be relevant here to recall that a similar approach to multispectral recording, using a large drum recorder, was used very successfully in the ground processing equipment (GPE) developed for the MSS.

DIGITAL PROCESSING

The digital processor required for the alternate system would be substantially larger than the one described for the basic system due to the

fact that data buffering for all six spectral bands must be provided. In this case, the linearity compensation would be done between the output of the data buffers and the input to the digital-to-analog converter (as was done in the MSS GPE), and would be no more complex than in the basic system.

Roughly estimated, the increase in cost of the digital processor for the alternate system over that for the basic system would be on the order of \$15,000 for one system, or \$3000 for each of 20 systems. The basic price of the K-661 image recorder, not including the modifications discussed, is approximately \$35,000, as compared to an estimated \$10,000 to \$15,000 for the LR-73. The saving due to elimination of the tape recorder is approximately \$25,000 to \$30,000. Thus, within present estimating accuracy, the costs of the basic system and the alternate system are the same.